DRAFT

Remedial Action Option Evaluation in Support of Intrinsic Remediation for the Jet Fuel Transfer Line Southwest of Building 412 and the POL Yard Volume 1: Text

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Wisconsin Air National Guard at Truax Field
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San Antonio, Texas

and

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REMEDIAL ACTION OPTION EVALUATION IN SUPPORT OF INTRINSIC REMEDIATION (NATURAL ATTENUATION)

for the

JET FUEL TRANSFER LINE SOUTHWEST OF BUILDING 412 AND THE POL YARD

WISCONSIN AIR NATIONAL GUARD at TRUAX FIELD

MADISON, WISCONSIN

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Prepared for:

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EXECUTIVE SUMMARY

This report presents the results of a remedial action option evaluation (RAE) performed by Parsons Engineering Science, Inc. (Parsons ES) at Truax Field Air National Guard Base, Wisconsin to evaluate the use of intrinsic remediation (natural attenuation) with long-term monitoring (LTM) as a remedial option for dissolved benzene, toluene, ethylbenzene, and xylene (BTEX) contamination in the shallow saturated zone in the vicinity of the former jet fuel transfer line southwest of Building 412 and the petroleum, oils, and lubricants (POL) yard (the site). Soil and ground water contamination is documented for the site, with contamination being present in the aqueous (i.e., dissolved) and gaseous phases and as residual light nonaqueous-phase liquid (LNAPL) within the aquifer matrix. There is no evidence of mobile LNAPL (free product) at this site. This study focused on the impact of dissolved BTEX on the shallow ground water system at the site. Site history and the results of soil and ground water investigations conducted previously are also summarized in this report.

Comparison of BTEX, electron acceptor, and biodegradation byproduct isopleth maps for ground water at the Truax Field site provides strong qualitative evidence of biodegradation of BTEX compounds. Geochemical data strongly suggest that biodegradation of fuel hydrocarbons is occurring at the site via aerobic respiration and the anaerobic processes of denitrification, iron reduction, sulfate reduction, and methanogenesis. In addition, patterns in the observed distribution of hydrocarbons, electron acceptors, and biodegradation byproducts provide additional indications that biodegradation is reducing dissolved BTEX concentrations in site ground water.

An important component of this study was an assessment of the potential for contamination in ground water to migrate from the source areas to potential receptors. The Bioplume II model was used to estimate the rate and direction of dissolved BTEX movement through the shallow saturated zone under the influence of advection, dispersion, sorption, and biodegradation. Input parameters for the Bioplume II model were obtained from existing site characterization data, supplemented with data collected by Parsons ES. Extensive site-specific data were used for model implementation. Model parameters that were not measured at the site were estimated using reasonable literature values.

The results of this study suggest that dissolved BTEX contamination present in ground water poses no significant risk to human health or the environment in its present, or predicted future, concentration and distribution. Parsons ES therefore recommends that intrinsic remediation with LTM be implemented as the appropriate remedial action to address dissolved BTEX contamination found in ground water at this site.

To verify the Bioplume II model predictions, Parsons ES recommends using four LTM wells and three point-of-compliance (POC) monitoring wells to monitor the long-term migration and degradation of the dissolved BTEX plume. Regular sampling and analysis of ground water from these sampling points will allow the effectiveness of intrinsic remediation to be monitored and should allow sufficient time to implement engineering controls to contain the plume if BTEX compounds are detected in the POC wells. Contaminant fate and transport model results indicate that these wells should be sampled on an annual basis for 15 to 20 years. Along with other analyses used to verify the effectiveness of intrinsic remediation, the ground water samples should be analyzed for BTEX compounds by US Environmental Protection Agency Method SW8020. If BTEX concentrations in ground water from the POC wells exceed the Wisconsin Department of Natural Resources enforcement standards of 5 micrograms per liter (µg/L) for benzene, 343 µg/L for toluene, 1,360 µg/L for ethylbenzene, or 620 µg/L for total xylenes, additional corrective actions may be required to remediate ground water at the site.

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SECTION 1

INTRODUCTION

This report was prepared by Parsons Engineering Science, Inc. (Parsons ES) and presents the results of a remedial action option evaluation (RAE) conducted to evaluate the use of intrinsic remediation (natural attenuation) for remediation of fuel-hydrocarbon-contaminated ground water at the former jet fuel transfer line southwest of Building 412 and the petroleum, oils, and lubricants (POL) yard, Truax Field Air National Guard Base (ANGB), Wisconsin (the Base). Previous investigations determined that fuel hydrocarbons had been released into the soil and shallow ground water at these sites. The main emphasis of the work described herein was to evaluate the potential for naturally occurring degradation mechanisms to reduce dissolved benzene, toluene, ethylbenzene, and xylene (BTEX) concentrations in ground water to levels that are protective of human health and the environment.

1.1 SCOPE AND OBJECTIVES

Parsons ES was retained by the United States Air Force Center for Environmental Excellence (AFCEE) to conduct site characterization and ground water modeling in support of intrinsic remediation with long-term monitoring (LTM).

The scope of work for this project involved the following tasks:

- Reviewing existing hydrogeologic and soil and ground water quality data for the site;
- Conducting supplemental site characterization activities to determine the nature and extent of soil and ground water contamination and to collect geochemical data in support of intrinsic remediation;
- Developing a conceptual hydrogeologic model of the shallow saturated zone, including the current distribution of contaminants;
- Determining if naturally occurring processes of contaminant attenuation and destruction are occurring in ground water at the site;
- Performing contaminant fate and transport modeling based on site hydrogeologic conditions using the Bioplume II model;

- Evaluating a range of model input parameters to determine the sensitivity of the model to those parameters and to consider several contaminant fate and transport scenarios;
- Determining if naturally occurring processes are sufficient to minimize BTEX plume expansion so that ground water quality standards can be met at a downgradient point of compliance (POC);
- Developing remedial action objectives (RAOs) and reviewing available remedial technologies;
- Using the results of modeling to recommend the most appropriate remedial option based on specific effectiveness, implementability, and cost criteria; and
- Providing an LTM plan that includes LTM and POC well locations and a sampling and analysis plan.

Site characterization activities in support of intrinsic remediation included cone penetrometer testing (CPT) in conjunction with laser-induced fluorometry (LIF); aquifer testing; soil sample collection and analysis; monitoring point installation; and ground water sampling and analysis from HydroPunch® locations, newly installed monitoring points, and existing monitoring wells.

Site-specific data were used to develop a fate and transport model for the site using the ground water flow and solute transport model Bioplume II and to conduct a preliminary exposure pathways analysis. The Bioplume II model was used to simulate the movement of BTEX in the shallow saturated zone under the influence of advection, dispersion, sorption, and biodegradation. As part of the RAE, this modeling effort had three primary objectives: 1) to predict the future extent and concentration of the dissolved contaminant plume by modeling the combined effects of advection, dispersion, sorption, and biodegradation; 2) to assess the possible threat to potential downgradient receptors based on comparison to regulatory ground water standards; and 3) to provide technical support for the intrinsic remediation with LTM remedial option during regulatory negotiations, as appropriate.

Bioventing and natural contaminant attenuation with LTM were evaluated during this RAE. All hydrogeologic and ground water chemical data necessary to evaluate these remedial options were collected under this program; however, the field work conducted under this program was oriented toward the collection of hydrogeologic data to be used as input into the Bioplume II ground water model in support of intrinsic remediation with LTM for restoration of fuel-hydrocarbon-contaminated ground water.

This report contains nine sections, including this introduction, and four appendices. Section 2 summarizes site characterization activities. Section 3 summarizes the physical characteristics of the study area. Section 4 describes the nature and extent of soil and ground water contamination and the geochemistry of soil and ground water at the site. Section 5 describes the Bioplume II model and design of the conceptual model for the site, lists model assumptions and input parameters, and describes sensitivity analysis, model output, and the results of the Bioplume II modeling. Section 6 presents a limited comparative analysis of remedial alternatives. Section 7 presents an LTM plan for the site. Section 8 presents the conclusions of this work and provides recommendations for further work at the site. Section 9 lists the references used to develop this document. Appendix A contains CPT logs, borehole logs, monitoring point installation records, borehole abandonment forms, and slug test results. Appendix B presents soil and ground water analytical results. Appendix C contains model input parameters and calculations related to model calibration. Appendix D contains Bioplume II model input and output in ASCII format on a diskette.

1.2 FACILITY BACKGROUND

The Base occupies approximately 155 acres in the southeastern portion of the Dane County Regional Airport in Madison, Wisconsin (Figure 1.1). The facility, which has operated since 1942, is located approximately 5 miles northeast of downtown Madison. The study area encompasses the former jet fuel transfer line between the area southwest of Building 412 and the POL yard (Figure 1.2). This area will be collectively referred to as the site. Soil and ground water contamination at the site has been attributed to leaks in the abandoned jet fuel transfer line, operation and maintenance activities associated with the hangar (Building 412), and fuel storage and transfer activities associated with the POL yard [Advanced Sciences, Inc. (ASI), 1991].

The POL facility includes four, steel 50,000-gallon underground storage tanks (USTs) next to Building 405, an abandoned 300-gallon waste oil UST, a 2,000-gallon waste oil UST, a bulk fuel receiving system, a refueling island for flightline fuel trucks, and the terminus of the former jet fuel transfer line (ASI, 1991). From approximately 1952 to 1973, the jet fuel transfer line was used to supply JP-4 jet fuel and aviation gasoline (AVGAS) to the flightline from the four 50,000-gallon USTs located at the POL. The jet fuel transfer line was abandoned in 1973; however, the four 50,000-gallon USTs and the 2,000-gallon waste oil

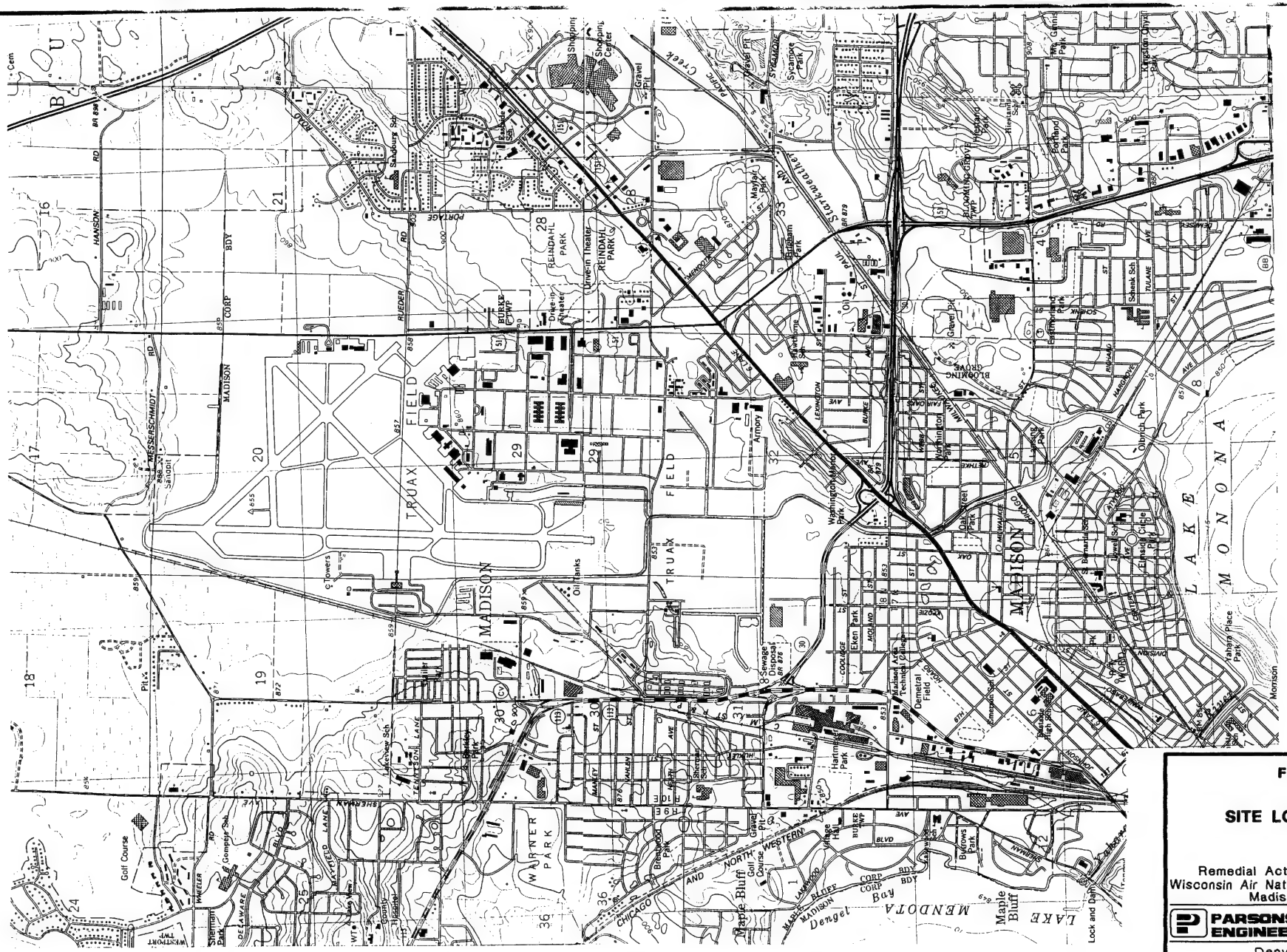

FIGURE 1.1

SITE LOCATION MAP

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

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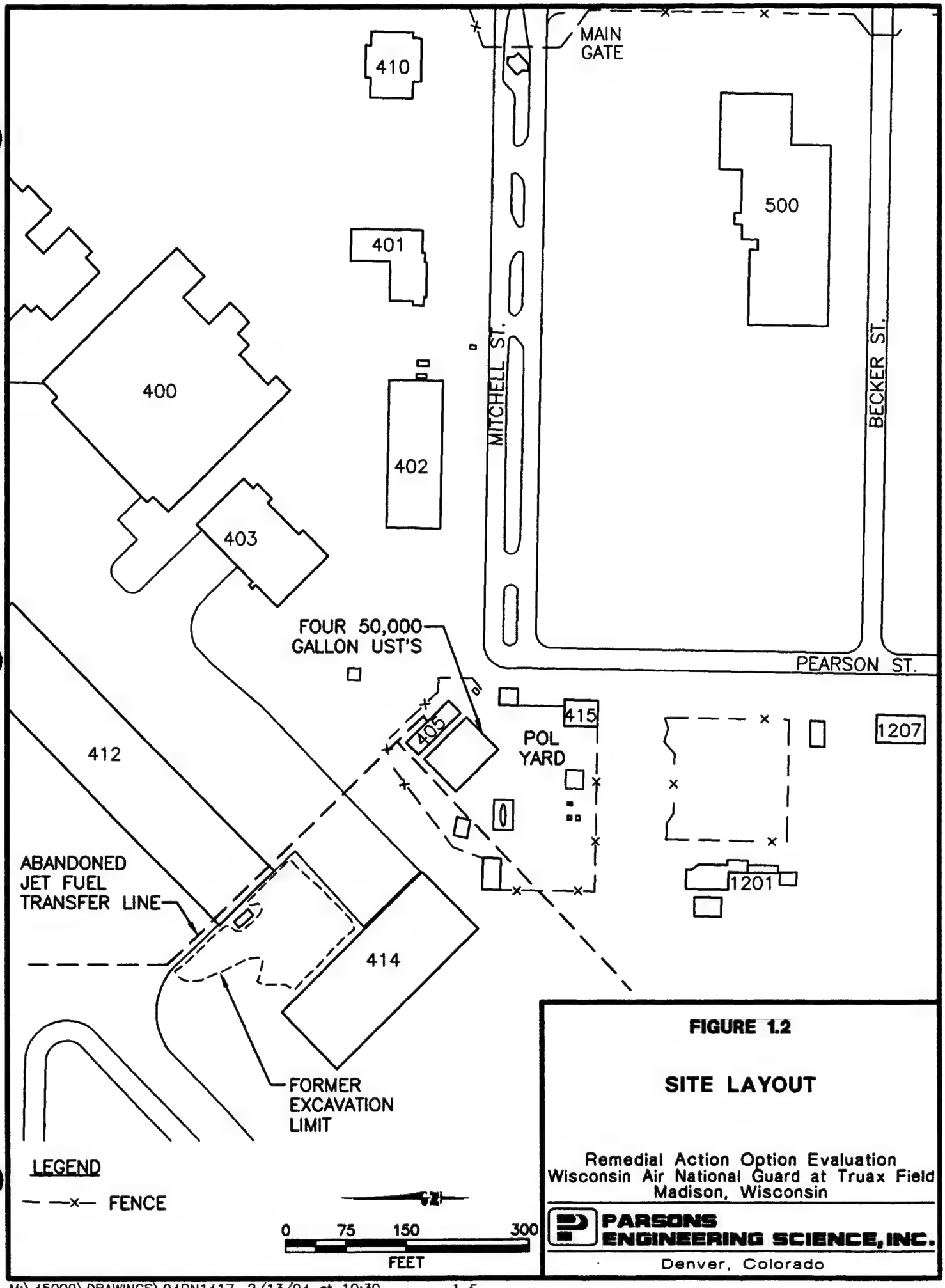

FIGURE 1.2

SITE LAYOUT

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

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UST remain in service [Peer Consultants, P. C. (Peer), 1988]. Fuel is currently transported between the POL and the flightline by truck. Volumetric tightness testing suggested that the active USTs are structurally sound, and ASI (1991) suggested that subsurface data gave no indication that the USTs had leaked.

On March 6, 1981, about 2,000 gallons of JP-4 jet fuel overflowed from one of the 50,000-gallon USTs onto the ground during a bulk fuel transfer (Peer, 1988). The spilled fuel was flushed into a 100-foot length of a dammed drainage ditch and allowed to soak into the soil. The following month the soils in the ditch were excavated to a depth of approximately 6 feet below ground surface (bgs) and laterally to the extent of odor detection. The excavated soils were removed from the site. Additional spills at the POL yard were not identified in previous investigation reports.

The discovery of contaminated soil and ground water in the area southwest of Building 412 during parking apron reconstruction consequently resulted in development of a remedial action plan (RAP), approved by the Wisconsin Department of Natural Resources (WDNR) to remove and treat the contaminated soils [Dames & Moore, 1992b; Nine Springs Environmental Consultants, Inc. (Nine Springs), 1994]. During fall 1993, approximately 3,000 cubic yards of soil were excavated from ground surface to ground water (approximately 5 to 6 feet bgs) over the area depicted in Figure 1.2. Soils determined to be contaminated were treated onsite using low-temperature thermal desorption. The excavation was backfilled with both clean, untreated excavated soil and clean, thermally treated soil (Nine Springs, 1994). The quantity of jet fuel released into the soils along the jet fuel transfer line, and in particular southwest of Building 412, is unknown. Data presented by Dames & Moore (1992b) suggest that soil contamination from this release extends no more than 50 feet beneath Building 412 and the concrete apron southeast of the source area.

The results of soil and ground water investigations at the site have been documented in several reports, including:

- Installation Restoration Program (IRP) Preliminary Assessment (Peer Consultants, 1988);
- Rapid Response Initiative, Site Assessment Report (ASI, 1991);
- Subsurface Investigation Report (Dames & Moore, 1992a);

- Remedial Action Plan (RAP) for Soils (Dames & Moore, 1992b);
- RAP Addendum Soil Vapor Extraction System (Nine Springs, 1993); and
- Remedial Action Summary Report, Soil Remediation (Southwest of Building 412) (Nine Springs, 1994).

The site-specific data presented in Sections 3, 4, and 5 are based on a review of these documents and on data collected by Parsons ES under this program.

SECTION 2

SITE CHARACTERIZATION ACTIVITIES

This section presents the methods used by Parsons ES personnel to collect site-specific data at the Base. To meet the requirements of the intrinsic remediation demonstration, additional data were required to evaluate near-surface geology, aquifer properties, and the nature and extent of soil and ground water contamination. Site characterization activities included performing CPT with LIF; measuring and estimating hydrogeologic parameters (static ground water levels, ground water gradient, ground water flow direction, and hydraulic conductivity); installing monitoring points; sampling and analysis of soils from hand-augered boreholes and CPT pushes; and sampling and analysis of ground water from HydroPunch® locations, newly installed monitoring points, and existing monitoring wells. The activities listed above were used to collect the following physical and chemical hydrogeologic data:

- Depth from measurement datum to the water table or potentiometric surface in monitoring wells and monitoring points;
- Rate of change of water elevation following rapid depression or elevation of water level in a monitoring well;
- Location of potential ground water recharge and discharge areas;
- Stratigraphy of subsurface media;
- Extent of residual-phase petroleum hydrocarbon contamination in soils;
- Concentrations of dissolved oxygen (DO), nitrate, ferrous iron, sulfate, methane, chloride, and total organic carbon (TOC) in ground water;
- Temperature, specific conductance, reduction/oxidation (redox) potential, total alkalinity, and pH of ground water;
- Concentrations of BTEX, trimethylbenzene (TMB), total volatile petroleum hydrocarbon (TVH), and total extractable petroleum hydrocarbon (TEH) in ground water and soil; and
- TOC concentrations in select soil samples.

In addition to the work conducted under this program, complementary site characterization data were previously collected by Peer, Dames & Moore, and Nine Springs during site investigations and soils remediation. These activities included soil sampling from hollow-stem auger boreholes using split-spoon samplers and from excavation sidewalls; field screening of soil samples, ground water sampling from monitoring wells installed through hollow-stem augers; slug testing; and measuring static ground water levels. Previously collected data and data collected under this program were integrated to develop the conceptual site model and to aid interpretation of the physical setting (Section 3) and contaminant distribution (Section 4).

The following sections describe the procedures that were followed when collecting site-specific data during the field work phase of the RAE. Additional details regarding investigative activities are presented in the draft work plan (Engineering-Science, Inc., 1994a).

2.1 CONE PENETROMETRY, MONITORING POINT INSTALLATION, AND SOIL SAMPLING ACTIVITIES

CPT-related activities took place between September 12 and September 16, 1994. CPT, soil sampling, and ground water monitoring point installation were accomplished using the procedures described in the following paragraphs.

Subsurface conditions at the site were characterized using CPT coupled with LIF. Cone penetrometry is an expeditious and effective means of analyzing the stratigraphy at a site by measuring the resistance of different soil types against the conical probe of the penetrometer as it is pushed into the subsurface. The resistance on the pressure tip and friction sleeves on the side of the cone is then correlated using previously collected soil data or soil cores collected to calibrate the CPT readings to the lithologies present at the site. Methodologies for the collection of soil samples are described in Section 2.1.3. The purpose of the LIF/CPT sampling at the site was to determine subsurface stratigraphy and to help delineate the extent of petroleum hydrocarbon contamination.

CPT was conducted using the US Army Corps of Engineers' (USACE's) cone penetrometer truck. This equipment consists of an instrumented probe that is forced into the ground using a hydraulic load frame mounted on a heavy truck, with the weight of the truck

providing the necessary reaction mass. The penetrometer equipment is housed in a stainless steel, dual-compartment body mounted on a 43,000-pound, triple-axle Kenworth™ truck chassis powered by a turbo-charged diesel engine. The weight of the truck and equipment is used as ballast to achieve the overall push capability of 39,000 pounds. This push capacity may be limited in tight soils by the structural bending capacity of the 1.8-inch outside-diameter (OD) push rods, rather than by the weight of the truck (1.4-inch-OD pushrods are used for some CPT applications). The current 39,000-pound limitation is intended to minimize the possibility of push-rod buckling. Penetration force is supplied by a pair of large hydraulic cylinders bolted to the truck frame.

The penetrometer probe is of standard dimensions, having a 1.8-inch-OD, 60-degree conical point with sacrificial tip, and an 8.0-inch-long by 1.8-inch-OD friction sleeve. Inside the probe, two load cells independently measure the vertical resistance against the conical tip and the side friction along the sleeve. Each load cell is a cylinder of uniform cross-section which is instrumented with four strain gauges in a full-bridge circuit. Forces are sensed by the load cells, and the data are transmitted from the probe assembly via a cable running through the push tubes. The analog data are digitized, recorded, and plotted by computer in the penetrometry truck. A grout tube also runs down the push cylinder to allow the introduction of bentonite or cement/bentonite grout into the hole in order to seal the CPT hole. The USACE CPT is not equipped to monitor pore pressure; therefore, the location of the water table was not be measured using the CPT apparatus. Evaluation of point and sleeve stresses can often provide an estimated depth to ground water. The penetrometer was usually advanced vertically into the soil at a constant rate of 2 centimeters per second, although this rate was sometimes reduced when gravel or hard layers were encountered. Penetration, dissipation, and resistivity data were used to determine site stratigraphy in the field.

The known propensity of aromatic hydrocarbons to fluoresce under ultraviolet wavelengths has allowed the use of LIF technology, in conjunction with CPT technology, to detect soil characteristics and hydrocarbon contamination simultaneously. The LIF system has a 0.25-inch sapphire window in the side of the cone that allows a laser to scan the soil for fluorescent compounds as the LIF penetrometer rod pushes through soil. Assuming that aromatic hydrocarbons are simultaneously solvenated with other fuel-hydrocarbon constituents, the magnitude of aromatic fluorescence is indicative of hydrocarbon contamination in a soil matrix. Fiber optic cables connected to the laser spectrometer, and a

6-pair electrical conductor connected to the CPT data acquisition system, are routed through the interior of the push tubes to the CPT probe.

The basic components of a LIF instrument are a nitrogen laser, a fiber optic probe, a monochromator for wavelength resolution of the return fluorescence, a photomultiplier tube to convert photons into an electrical signal, a digital oscilloscope for waveform capture, and a control computer. The fiber optic probe for the cone penetrometer consists of delivery and collection optical fibers, a protective sheath, a fiber optic mount within the cone, and a 0.25-inch sapphire window (Figure 2.1). The wavelength used in the USACE CPT LIF system gives the strongest fluorescence signal (attributable to the presence of contamination) for naphthalene and heavier long-chained hydrocarbons. Thus, while the LIF is not entirely appropriate for detecting the fluorescence of BTEX, it is useful for defining soil contamination because the heavier long-chained hydrocarbons are more likely to sorb to the soil matrix.

The results of each LIF/CPT push were available 2 or 3 minutes after the completion of each hole. Graphs showing cone resistance, sleeve friction, fluorescence intensity, and wavelength were plotted by USACE staff at the conclusion of each penetration and presented to the Parsons ES field scientist in order to allow investigative decisions to be based on the most current information.

2.1.1 CPT and Ground Water Monitoring Point Locations

CPT and/or ground water monitoring point installation was performed at 20 locations in the vicinity of the site. All CPT and/or monitoring point locations are indicated on Figure 2.2. At 8 of the 20 sites, ground water monitoring points were installed. At two locations, HydroPunch® samplers were used to collect ground water samples. At the remaining CPT sites, only soil characteristics and LIF data were recorded. Nested ground water monitoring points (with screens at different depths) were installed at four of the CPT locations. Soil samples for laboratory analysis were collected at nine of the sites. Table 2.1 presents details regarding CPT-related activity undertaken at each location. CPT locations were selected to provide the hydrogeologic data necessary for successful implementation of the Bioplume II model.

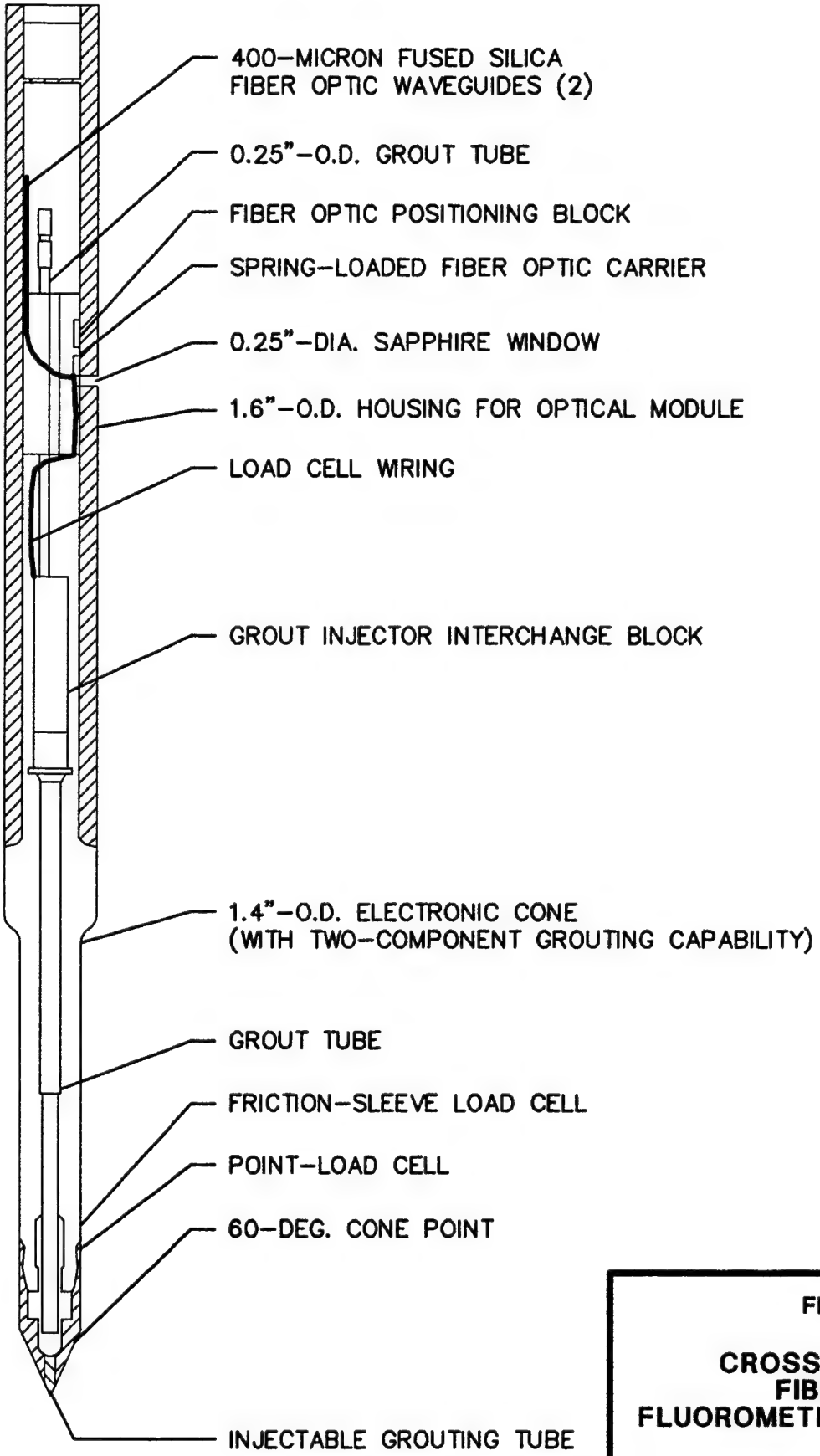

FIGURE 2.1

CROSS-SECTION OF FIBER OPTIC FLUOROMETRY PENETROMETER

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

M:\45009\DRAWINGS\95DN0106, 2/13/95 at 10:45

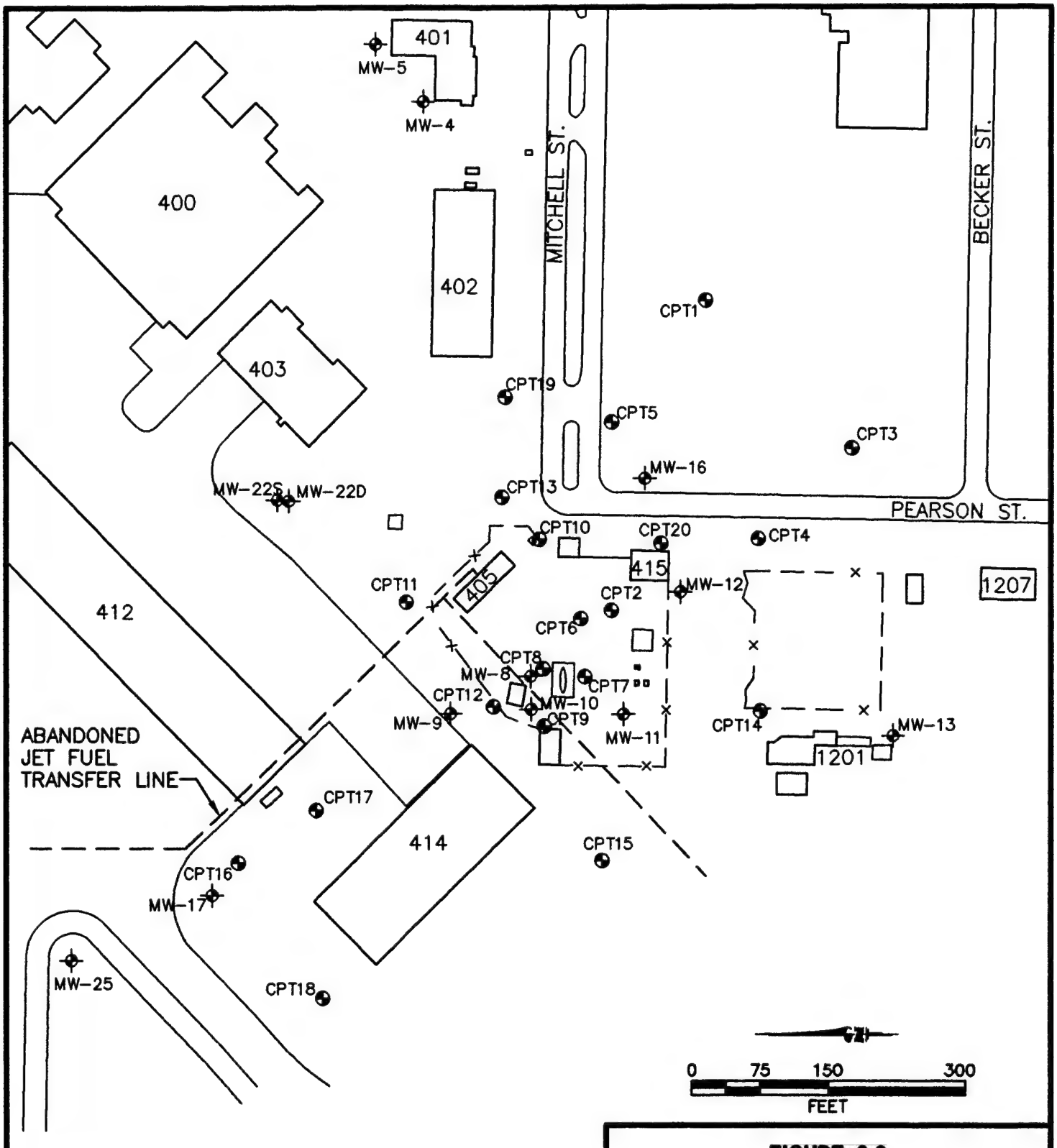

FIGURE 2.2

MONITORING WELL AND CPT SAMPLING LOCATIONS

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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TABLE 2.1

CPT ACTIVITY SUMMARY
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Location	Ground Elevation (ft msl) [a/]	Total Depth (ft bgs) [b/]	Depth to Top of Screen (ft bgs)	Depth to Base of Screen (ft bgs)	LIF Profile?	Soil Sample Intervals (ft bgs)
CPT1	861.2	25.1	NA[c/]	NA	Y	NS[d/]
CPT1S		11.0	7.7	11	N	NS
CPT1D		21.0	17.7	21	N	NS
CPT2		25.5	NA	NA	Y	7 - 7.5
CPT3		15.2	NA	NA	Y	5 - 5.5
HP-CPT3		12.5	9.2	12.5	N	NS
CPT4	858.2	15.1	NA	NA	Y	NS
CPT-4S		9.5	6.2	9.5	N	NS
CPT-4D		19.5	16.2	19.5	N	NS
CPT5	858.5	15.0	NA	NA	Y	NS
CPT5S		10.4	7.1	10.4	N	NS
CPT5D		20.4	17.1	20.4	N	NS
CPT6		19.7	NA	NA	Y	NS
CPT7		16.3	NA	NA	Y	7.8 - 8.3
CPT8		19.3	NA	NA	Y	7.5 - 8
CPT9		19.8	NA	NA	Y	5.5 - 6
CPT10		20.0	NA	NA	Y	NS
CPT11		19.9	NA	NA	Y	6.5 - 7
HP-CPT11		12.5	9.2	12.5	N	NS
CPT12		16.7	NA	NA	Y	NS
CPT13		19.5	NA	NA	Y	NS
CPT14		15.2	NA	NA	Y	NS
CPT15	856.3	23.0	NA	NA	Y	NS
CPT15S		9.5	6.2	9.5	N	NS
CPT16		16.4	NA	NA	Y	NS
CPT17	854.5	22.9			Y	5 - 5.5
CPT17S		6.5	3.2	6.5	N	NS
CPT17D		16.5	13.2	16.5	N	NS
CPT18	855.8	15.1	NA	NA	Y	4.5 - 5
CPT18S		7.0	3.7	7	N	NS
CPT19	858.9	15.0	NA	NA	Y	NS
CPT19S		11.0	7.7	11	N	NS
CPT20	6.4	15.1	NA	NA	N	6.8 - 7.3
CPT20S	6.4	10.5	7.2	10.5	N	NS

[a/] ft msl = feet above mean sea level.

[b/] ft bgs = feet below ground surface.

[c/] NA = not applicable

[d/] NS = no soil sample collected

All CPT holes not finished as monitoring points were abandoned immediately after completion, per section NR141.25 of the Wisconsin Administrative Code. As the push cylinder was withdrawn, the hole was sealed with Portland® cement grout injected through the grout tube. Borehole abandonment forms are provided in Appendix A.

2.1.2 Ground Water Monitoring Point Installation Procedures

This section describes the procedures and equipment used for installation of new ground water monitoring points with the CPT apparatus.

2.1.2.1 Pre-Installation Activities

All necessary digging or drilling permits were obtained prior to mobilizing to the field. In addition, all utility lines were located, and proposed drilling locations were cleared prior to any drilling activities.

2.1.2.2 Equipment Decontamination Procedures

After sampling at each CPT location, CPT push rods were cleaned with the CPT steam-cleaning system (rod cleaner) as the rods were withdrawn from the ground. A vacuum system located beneath the CPT truck was used to recover cleaning water. Use of this system resulted in nearly 100-percent recovery of steam-cleaning rinseate from the rod cleaner. Rinseate was generated only as the rods moved past the cleaner, thereby minimizing liquid waste generation. Rinseate was collected in a 55-gallon drum provided by USACE. The filled 55-gallon drum was then disposed of by BT^2, Inc. of Madison, Wisconsin, per their standing agreement with the local wastewater utility.

Water used in equipment cleaning or grouting was obtained from an onsite potable water supply. Water use approval was verified by contacting the appropriate facility personnel. Precautions were taken to minimize any impact to the surrounding area that might result from decontamination operations.

Fuel, lubricants, and other similar substances used for CPT operation were handled in a manner consistent with accepted safety procedures and standard operating practices. Well

completion materials were not stored near or in areas that could be affected by these substances.

2.1.2.3 Monitoring Point Installation

Ground water monitoring points were installed at eight locations under this program. Detailed well installation procedures are described in the following paragraphs. At four locations (CPT1, CPT4, CPT5, and CPT17), two nested points (each screened at a different depth) were installed. At each location, the point with the shallowest screened interval was designated with the suffix "S", while the deep point was designated with the suffix "D" (e.g., CPT5S or CPT5D). Single points were installed at the remaining four locations (CPT15S, CPT18S, CPT19S, and CPT20S). Monitoring point completion diagrams are included in Appendix A.

2.1.2.3.1 Monitoring Point Materials Decontamination

Well completion materials were inspected by the field hydrogeologist and determined to be clean and acceptable prior to use. All well completion materials were factory sealed. Materials were inspected for possible external contamination before use. Materials that could not be cleaned to the satisfaction of the field hydrogeologist were not used.

2.1.2.3.2 Monitoring Point Screen and Casing

Upon completion of CPT to the proper termination depth, monitoring point casing was installed. Construction details were noted on a Monitoring Point Installation Record form. This information became part of the permanent field record for the site.

Blank monitoring point casing was constructed of either Schedule 40 polyvinyl chloride (PVC) with an inside diameter (ID) of 0.5 inch. All casing sections were flush-threaded; glued joints were not used. The casing at each monitoring point was fitted with a PVC top cap. Because the points were finished at grade, the top cap was not vented.

Monitoring point screens and blank casing sections were constructed of flush-threaded, Schedule 40 PVC with an ID of 0.5 inch. The screens were factory slotted with 0.010-inch openings. At nested monitoring points, the shallow screen was placed across or just below

the water table, and the deep screen was placed 9 to 10 feet below the shallow screen. Where single points were installed, the screen was placed across or just below the water table.

Field personnel verified and recorded the hole depth and the lengths of all casing sections. All lengths and depths were measured to the nearest 0.1 foot.

2.1.2.3.3 Flush-Mount Protective Cover

Each monitoring point was completed with an at-grade protective cover. In all locations, the at-grade covers were cemented in place using concrete. All wells were completed with concrete pads that slope gently away from the protective casing to facilitate runoff during precipitation events. The space inside the protective covers (below the top of the PVC) was filled with sand to allow drainage of any precipitation that might collect within the cover.

2.1.2.4 Monitoring Point Development

Before being sampled, newly installed monitoring points were developed. Typically, well development removes sediment from inside the well casing and flushes fines, cuttings, and drilling fluids from the sand pack and the portion of the formation adjacent to the well screen. Use of the CPT apparatus to place monitoring points eliminates cuttings, drilling fluids, and the use of a filter pack. As a result, development of monitoring points is primarily intended to minimize the amount of fine sediment that might accumulate in the casing.

Monitoring point development was accomplished using a peristaltic pump with dedicated high-density polyethylene (HDPE) tubing. The pump tubing was regularly lowered to the bottom of the well so that fines were agitated and removed from the well in the development water. Development was continued until 10 casing volumes of water were removed from the well and the pH, temperature, DO concentration, and redox potential of the ground water had stabilized. Well development waters in known or suspected areas of contamination were added to the 55-gallon drum containing CPT steam-cleaning wastes.

2.1.2.5 Monitoring Point Abandonment

As defined by section NR141.29 of the Wisconsin Administrative Code, monitoring points installed using the CPT equipment are temporary ground water monitoring wells and

should be abandoned within 120 days. However, Mr. Mike Schmoller of the WDNR Southern District Office granted one-time permission for the monitoring points to remain in place for possible future resampling. When use of the monitoring points for this project is terminated, they will be abandoned according to the requirements set forth in section NR141.25 of the Wisconsin Administrative Code.

2.1.2.6 Water Level Measurements

Water levels were measured at monitoring points with PVC casing. Measurements were made using an electric water level probe capable of recording to the nearest 0.01 foot. Additional water level measurements were also made in several existing monitoring wells.

2.1.2.7 HydroPunch® Installation

The CPT rig was used to advance a HydroPunch® ground water sampling probe at CPT3 and CPT11. The HydroPunch® is a hollow, stainless steel cylinder with a disposable tip, which can be attached to the CPT pushrods and driven to the desired sampling depth. A 3.3-foot teflon® screen was attached to the disposable tip and protected by the cylinder during the push. At the site, the pushrods were pushed so that the full length of the screen would be just below the water table, then the rods were raised approximately 3.3 feet to expose the screen. The HydroPunch® probes produced ground water fairly rapidly, and the points were purged and sampled following procedures described in Section 2.2.

2.1.3 Soil Sampling

Soil samples were obtained at four CPT locations (CPT2, CPT8, CPT11, and CPT17) using a Hoggen Toggler® sampling device. The sampler is coupled to the penetrometer rod and pushed into the soil with the same equipment used for CPT/LIF. While the Hoggen Toggler® cone is in position, soil is prevented from entering the sampling tube until the desired depth is achieved. When the sampler has been pushed to the depth at which the soil sample is to be taken, the sampling unit is raised a few inches and the Hoggen Toggler® apparatus is opened. After opening the Hoggen Toggler® attachment, a soil section is cut and the sampling apparatus is then pulled from the ground as quickly as possible. The Hoggen Toggler® sampling apparatus allows collection of 8-inch-long by 1-inch-ID continuous

samples. Recovery efficiencies for samples in saturated soils are often reduced, or the samples are compromised, because of spillage of the soil from the device after extraction. To mitigate this problem, soil samples were compressed *in situ* with the penetrometer and Hoggen Toggler® assembly to expel pore water before extraction.

Compressed soil samples were removed from the sampler and placed in clean glass jars for laboratory analysis. In addition to samples collected with the CPT, shallow soil stratigraphy was examined at five locations (CPT3, CPT7, CPT9, CPT18, and CPT-20) using a bucket auger. At these locations, soil samples were placed directly into jars after removal from the auger bucket. Soil sample locations and depths are summarized on Table 2.1.

Parsons ES field personnel observed CPT and monitoring point installation activities and maintained a log documenting any unusual conditions encountered during installation. Graphical results of each LIF/CPT push were plotted by the USACE at the conclusion of each penetration and were available minutes after the completion of each hole. The graphs showed cone resistance, sleeve friction, soil classification, fluorescence intensity, and maximum fluoresced wavelength. The real-time availability of the CPT information allowed the Parsons ES field scientist to make investigative decisions based on the most current information. Final CPT logs are presented in Appendix A. These logs indicate lithologic characteristics and contacts as indicated by CPT readings, as well as LIF data. In addition to CPT logs, logs of hand-augered holes are presented in Appendix A.

All soil sampling tools were cleaned onsite prior to use and between each sampling event with a potable water/phosphate-free detergent mix, a potable water rinse, and a distilled water rinse. All decontamination activities were conducted in a manner so that the excess water was contained and properly disposed of.

2.2 GROUND WATER SAMPLING

This section describes the procedures used for collecting ground water quality samples. In order to maintain a high degree of quality control (QC) during this sampling event, the procedures described in the site work plan (Engineering-Science, Inc., 1994a) and summarized in the following sections were followed.

Ground water sampling occurred during September 1994, and consisted of collecting ground water samples from new monitoring points, existing monitoring wells, and HydroPunch® locations. The procedures used to sample ground water monitoring wells are described in Section 2.2.3.2. In addition to the sampling events conducted under this program, ASI (1991) and Dames & Moore (1992a and 1992b) have conducted ground water sampling events at the site.

Activities that occurred during ground water sampling are summarized below:

- Assembly and preparation of equipment and supplies;
- Inspection of the well integrity, including
  - Protective cover, cap and lock,
  - External surface seal and pad,
  - Well casing, cap, and datum reference, and
  - Internal surface seal;
- Ground water sampling, including
  - Water level measurements,
  - Visual inspection of water,
  - Well casing evacuation, and
  - Sampling;
- Sample preservation and packaging, including
  - Sample preparation,
  - Onsite measurement of physical parameters, and
  - Sample labeling;
- Completion of sampling records; and
- Sample delivery to Evergreen Analytical, Inc. in Wheat Ridge, Colorado.

Detailed ground water sampling and sample handling procedures that were used are presented in following sections.

2.2.1 Ground Water Sampling Locations

Ground water samples were collected from existing monitoring wells, newly installed monitoring points, and HydroPunch® locations by Parsons ES personnel. Twelve new

monitoring points, including four nested pairs, were installed in the locations shown on Figure 2.2. HydroPunch® samples were collected at locations CPT3 and CPT11. After completion of well installation and development activities, these wells were sampled using a peristaltic pump with dedicated HDPE tubing. Ten previously existing monitoring wells were also sampled under this program. Existing wells that were sampled included MW-25, MW-17, MW-8, MW-9, MW-10, MW-11, MW-12, MW-13, MW-16, and MW-22S.

2.2.2 Preparation for Sampling

All equipment used for sampling was assembled and properly cleaned and calibrated (if required) prior to arriving in the field. In addition, all record-keeping materials were gathered prior to leaving the office.

2.2.2.1 Equipment Cleaning

All portions of sampling and test equipment that contacted the sample were thoroughly cleaned before use. This equipment included the water level probe and cable, lifting lines, test equipment for onsite use, and other equipment that contacted the samples. The following cleaning protocol was used:

- Cleaned with potable water and phosphate-free laboratory detergent;
- Rinsed with potable water;
- Rinsed with isopropyl alcohol;
- Rinsed with distilled or deionized water; and
- Air dried prior to use.

Any deviations from these procedures were documented in the field scientist's field notebook and on the ground water sampling form.

2.2.2.2 Equipment Calibration

As required, field analytical equipment was calibrated according to the manufacturers' specifications prior to field use. This requirement applied to direct-reading meters used for

onsite chemical measurements such as DO, pH, redox potential, and temperature, as well as for the Hach® meter used for other onsite analyses.

2.2.3 Sampling Procedures

Special care was taken to prevent contamination of the ground water and extracted samples through cross contamination from improperly cleaned equipment. Water level probes and cable used to determine static water levels and well total depths were thoroughly cleaned before and after field use and between uses at different sampling locations according to the procedures presented in Section 2.2.2.1. In addition, a clean pair of new, disposable nitrile gloves was worn each time a different well was sampled.

Sampling at ground water monitoring and HydroPunch® locations followed the procedures outlined in the following sections. Samples from monitoring points were collected after development, so the purging step was omitted.

2.2.3.1 Preparation of Location

Prior to starting the sampling procedure, the area around the well was cleared of foreign materials, such as brush, rocks, and debris. These procedures prevented sampling equipment from inadvertently contacting debris around the monitoring well.

2.2.3.2 Water Level and Total Depth Measurements

Water levels were measured at all existing wells before sampling began. In wells in and near the source areas, an Oil Recovery Systems™ oil/water interface probe was used to measure the depth to free product and the oil/water interface. Free hydrocarbons were not detected in any of the wells.

Prior to removing any water from a well, the static water level was measured. An electrical water level probe was used to measure the depth to ground water below the well datum to the nearest 0.01 foot. After measurement of the static water level, the water level probe was lowered to the bottom of the well for measurement of total well depth (recorded to the nearest 0.01 foot). On the basis of these measurements, the volume of water to be purged from the wells was calculated.

2.2.3.3 Well Purging

At least three times the calculated casing volume was removed from each well prior to sampling. Purging continued until the pH, temperature, DO concentration, and redox potential of the ground water did not change during a three-minute period. A peristaltic pump with dedicated HDPE tubing was used for well evacuation.

During purging, a sample of the ground water was placed in a sealed container for headspace analysis using a photoionization detector (PID). Purge water that produced a PID headspace reading over 5 parts per million on a volume per volume basis (ppmv) was placed in the drum containing CPT steam-cleaning wastes. Purge water producing PID reading below 5 ppmv were spilled onto a paved surface to facilitate evaporation.

2.2.3.4 Sample Extraction

A peristaltic pump with dedicated HDPE tubing was used to extract ground water samples from each well. The sample was transferred directly into the appropriate sample container. The water was carefully poured down the inner walls of the sample bottle to minimize aeration of the sample. Sample bottles for TVH, BTEX, and TMB analyses were filled so that there was no headspace or air bubbles within the container.

2.2.4 Onsite Chemical Parameter Measurement

2.2.4.1 Dissolved Oxygen Measurements

DO measurements were taken using an Orion® model 840 DO meter in a flow-through cell at the outlet of the peristaltic pump. DO concentrations were recorded after the readings stabilized, and in all cases represent the lowest DO concentration observed.

2.2.4.2 pH, Temperature, and Redox Potential Measurements

Because the pH, temperature, and redox potential of the ground water change significantly within a short time following sample acquisition, these parameters were measured in the field, in the same flow-through cell in which DO was measured. The measured values were recorded in the ground water sampling record.

2.2.5 Sample Handling

2.2.5.1 Sample Preservation

The analytical laboratory (Evergreen Analytical, Inc.) provided pre-preserved sample containers where appropriate.

2.2.5.2 Sample Container and Labels

Sample containers and appropriate container lids were provided by the analytical laboratory. The sample containers were filled as described in Sections 2.2.3.4, and the container lids were tightly closed. The sample label was firmly attached to the container side, and the following information was legibly and indelibly written on the label:

- Facility name;
- Sample identification;
- Sample type (ground water);
- Sampling date;
- Sampling time;
- Preservatives added; and,
- Sample collector's initials.

2.2.5.3 Sample Shipment

After the samples were sealed and labeled, they were packaged for transport to the analytical laboratory in Wheat Ridge, Colorado. The following packaging and labeling procedures were followed:

- Sample was packaged to prevent leakage or vaporization from its container;
- Samples were cushioned to avoid breakage; and
- Ice was added to the container to keep the samples cool.

The packaged samples were delivered by overnight courier to the laboratory. Chain-of-custody procedures outlined in the project work plan (Engineering-Science, Inc., 1994a) were followed. Delivery occurred as soon as possible after sample acquisition.

2.3 AQUIFER TESTING

Slug tests are single-well hydraulic tests used to determine the hydraulic conductivity of an aquifer in the immediate vicinity of the tested well. Slug tests can be used for both confined and unconfined aquifers that have a transmissivity of less than 7,000 square feet per day (ft^2/day). Slug testing can be performed using either a rising head or a falling head test. Both rising head and falling head tests were used at this site. Slug tests were performed in monitoring wells MW-13, MW-16, and MW-17 (Figure 2.2). Detailed slug testing procedures are presented in the *Draft Technical Protocol for Implementing the Intrinsic Remediation with Long-Term Monitoring Option for Natural Attenuation of Dissolved-Phase Fuel Contamination in Ground Water* (Wiedemeier *et al.*, 1994), hereafter referred to as the Technical Protocol document.

2.3.1 Slug Test Data Analysis

Data obtained during slug testing were analyzed using AQTESOLV software and the methods of Bouwer and Rice (1976) and Bouwer (1989) for unconfined conditions. The results of slug testing are presented in Section 3.3.

2.4 SURVEYING

After installation, all CPT locations were surveyed by USACE personnel. The horizontal locations were measured relative to a Base datum, and horizontal locations of previously installed wells were measured to allow conversion to state plane coordinates. Elevations of the top of the PVC well casing and adjacent ground surface were also measured relative to that datum. Owing to errors in the vertical portion of the USACE survey, vertical locations of the PVC casing and ground surface were resurveyed by BT^2, Inc. of Madison, Wisconsin. At this time, elevations were measured relative to existing wells tied to a US Geological Survey (USGS) mean sea level (msl) datum. Datum and ground surface elevations were surveyed to the nearest 0.01 foot. The previously reported elevation for the PVC casing of wells MW-17 and MW-12 (ASI, 1990) were used as local elevation benchmarks.

SECTION 3

PHYSICAL CHARACTERISTICS OF THE STUDY AREA

This section incorporates data collected by Parson ES in September 1994 with data documented in previous reports on Truax Field ANGB. Investigative techniques used to determine the physical characteristics of the site were discussed in Section 2.

3.1 SURFACE FEATURES

3.1.1 Topography and Surface Water Hydrology

The Base is located near the center of the Central Lowland Physiographic Province of the Interior Plains, a region characterized by a large area of plains, slight local relief, and relatively low altitudes of 500 to 2,000 feet msl. The province displays widespread topographic effects of glaciation (ASI, 1991), and the Base lies on a broad flat plain that is the former location of Glacial Lake Yahara. The Base lies between 855 and 860 feet msl (USGS, 1985a and 1985b), and much of the ground surface is paved. A topographic map of the Base area is presented in Figure 1.1.

Major surface water features in the area include Lakes Mendota (1.3 miles southwest of the Base) and Monona (1.5 miles south of the Base). Two other large lakes, Kegonsa and Waubesa, are located south of the City of Madison. Cherokee Marsh is located approximately 0.5 mile north-northwest of the Base, on the northern side of the Dane County Regional Airport. A second wetland area is located in Warner Park approximately 1 mile west of the Base (USGS, 1985a and 1985b). Surface water flow and runoff on the Base is channeled by excavated ditches and culverts that are routed to Starkweather Creek via an outfall on the southern perimeter of the Base. The Starkweather Creek drainage follows the northern, western, and southern boundaries of the Dane County Regional Airport and flows south to its discharge point at Lake Monona (Peer, 1988).

3.1.2 Manmade Features

Much of the land surface at the site is paved or covered with buildings. Figure 1.2 shows the locations of buildings and some of the paved areas. Unpaved areas of note include the area of the excavation indicated in Figure 1.2, a low grassy area in the vicinity of MW-9, the southern portion of the POL yard, and a grassy strip along the west side of Pearson Street. Precipitation either infiltrates directly into the ground or runs off covered or paved areas to unpaved areas where it can then infiltrate. It is not known if utility corridors influence ground water movement. However, the relatively high permeability of the sediments in the vicinity of the water table should prevent such preferential migration.

3.2 REGIONAL GEOLOGY AND HYDROGEOLOGY

Glacial deposits cover all but the southwestern quarter of Dane County. The Base is located on a wedge of glacial drift approximately 300 feet thick, which overlies the Mount Simon Sandstone. The glacial material is predominantly sands and silts with interbedded clays and gravels, occupying the preglacial Yahara River Valley. The Base is approximately 15 miles east and 15 miles northeast of the terminal moraines marking the southwestern extent of glaciation during the Wisconsinan Period (ASI, 1991).

The uppermost glacial deposits near the Base are mostly lacustrine silts and clays deposited in the former Lake Yahara, which existed during a glacial period that ended approximately 11,500 years ago (Clayton *et al.*, 1991). Beneath the fine-grained lake sediments, outwash sands and gravels can generally be found near former glacial lake shorelines and within a few feet of the surface (ASI, 191).

Ground water is approximately 5 to 10 feet below ground surface (bgs) at the Base. Glacial deposits are recharged directly by precipitation and infiltration from the surface. Regionally, ground water is found in the glacial deposits and underlying formations. Sandstones of the Trempealeau Group, the deeper Tunnel City Group, and the still deeper Elk Mound Group comprise the principal water supply aquifers in Dane County. The Mount Simon Sandstone, which underlies the glacial deposits at the Base, is the lowermost formation of the Elk Mound Group (Ostrom, 1967). Regional ground water flow in the bedrock and the glacial deposits is reportedly south-southwest toward Lake Mendota, although extensive pumping of local high-capacity wells has imposed a downward component to ground water flow and has locally affected the direction of ground water flow (Peer, 1988). The pumping has also resulted in a

reduction of ground water discharge to wetlands, lakes, and streams (Peer, 1988). The nearest identified ground water use is a group of several wells, located 1.5 miles southwest of the Base, which serve the Oscar Mayer processing plant (Peer, 1988).

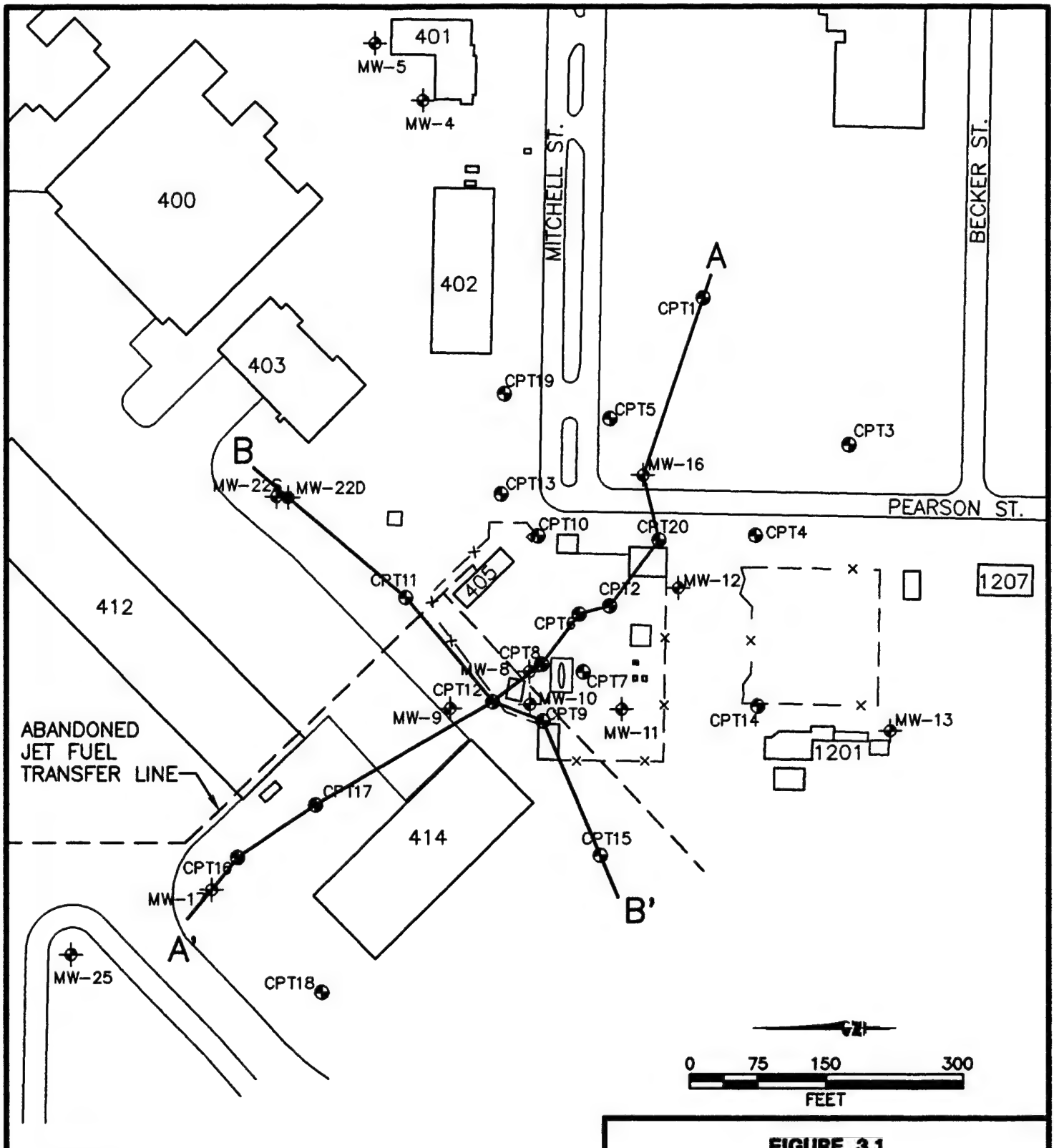
3.3 SITE GEOLOGY AND HYDROGEOLOGY

3.3.1 Lithology and Stratigraphic Relationships

During the course of previous investigations in the site area (ASI, 1991; Dames & Moore, 1992a and 1992b), many soil boreholes and monitoring wells have been installed. In general, subsurface soil observed at the site consists of a clay or silty clay to a depth of 3 to 6 feet bgs, underlain by a fine- to medium-grained, well-rounded, grayish-brown sand with occasional silty or gravelly intervals. In some locations silty, sandy, gravelly fill overlies the silty clay layer; in other locations, the fill is thick enough that it directly overlies the sand unit. The sand unit appears relatively homogeneous, and the geologic log from monitoring well MW-22D indicates that the unit extends to a depth of at least 40 feet bgs (Dames & Moore, 1992a).

Soil stratigraphy encountered during CPT and hand augering activities conducted by Parsons ES and USACE in September 1994 was similar to that encountered by the previous investigators. As indicated by CPT logs and confirmed by soil samples collected using a hand auger, clay, silt, or silty clay is typically present from the ground surface to depths of 4 to 7 feet bgs. In the vicinity of the POL Yard and at CPT1, sand units up to 2.5 feet thick are interbedded in the fine-grained deposits. Sandy and/or gravelly fill is present at the surface in some locations, particularly where pavement is present. In the area south of Building 412, fill is up to 6 feet thick in the area that was excavated in fall 1993. Beneath the fill and the fine-grained units, the sand unit described previously is present. This unit appears relatively uniform on the CPT logs, with scattered thin lenses of silty or gravelly sand.

These stratigraphic relationships are illustrated by hydrogeologic sections A - A' and B - B', which include data from previously installed wells and CPT data collected in September 1994. Figure 3.1 shows the locations of these sections. Figure 3.2 presents hydrogeologic section A - A', which is approximately parallel to the direction of ground water flow. Figure 3.3 presents hydrogeologic section B - B', which is approximately perpendicular to the direction of ground water flow.



LEGEND

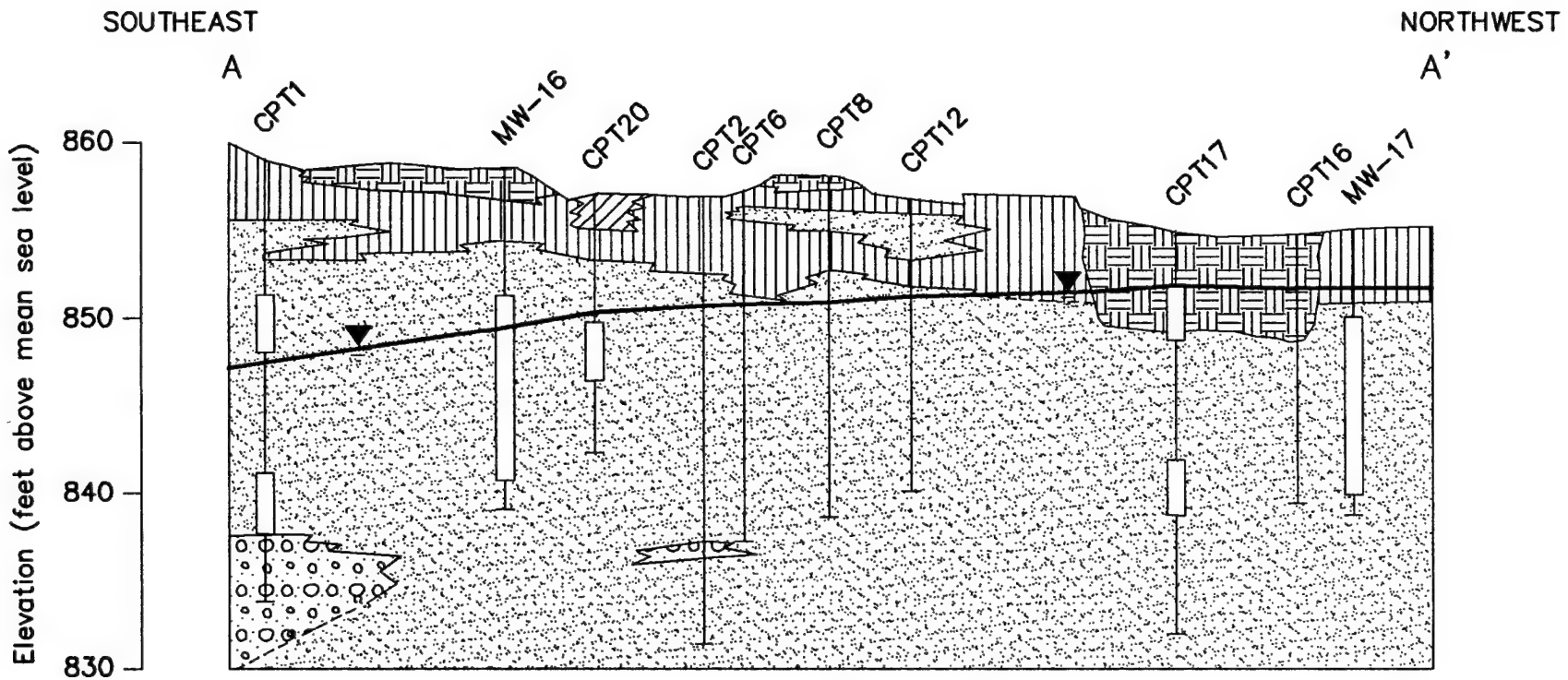
- MW-4 — MONITORING WELL
- CPT1 — CPT OR GROUND WATER MONITORING POINT
- — —×— — FENCE
- A—A' — LOCATION OF HYDORGEOLOGIC CROSS-SECTION

FIGURE 3.1

LOCATION OF HYDROGEOLOGIC CROSS-SECTIONS

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado



VERTICAL EXAGGERATION 15x

0 150 300

FEET

LEGEND

- Contact
- Approximate Contact
- CPT1 — Well/CPT Identification
- Well/CPT Screen
- Bottom of Borehole
- Approximate Location of Water Table
- FILL. Mostly sand and gravel, with varying amounts of silt and clay.
- Dark brown to grey to black CLAY, SILTY CLAY, and CLAYEY SILT, with occasional sandy intervals.
- Light brown to grey–brown SAND. Generally fine to medium grained. Occasional silty or gravelly intervals.
- GRAVELLY SAND as indicated by CPT.
- Dark brown to dark grey SILT or SILTY SAND.

FIGURE 3.2

HYDROGEOLOGIC CROSS-SECTION A-A'

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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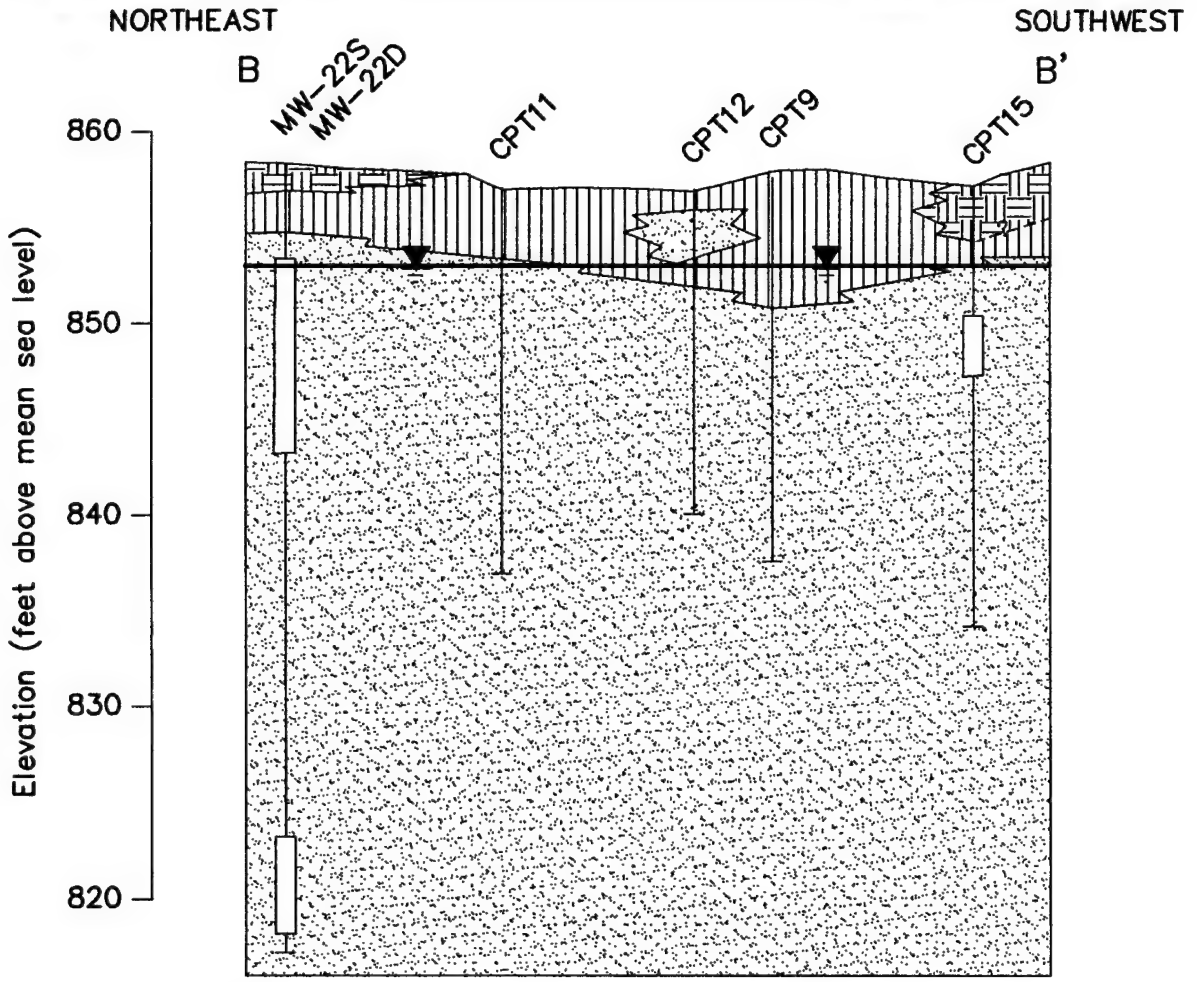

VERTICAL EXAGGERATION 15x

0 150 300

FEET

LEGEND

- Contact
- Approximate Contact
- CPT15 — Well/CPT Identification
- Well/CPT Screen
- Bottom of Borehole
- Approximate Location of Water Table

- FILL. Mostly sand and gravel, with varying amounts of silt and clay.
- Dark brown to grey to black CLAY, SILTY CLAY, and CLAYEY SILT, with occasional sandy intervals.
- Light brown to grey–brown SAND. Generally fine to medium grained. Occasional silty or gravelly intervals.

FIGURE 3.3

HYDROGEOLOGIC CROSS-SECTION B-B'

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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3.3.2 Ground Water Hydraulics

3.3.2.1 Flow Direction and Gradient

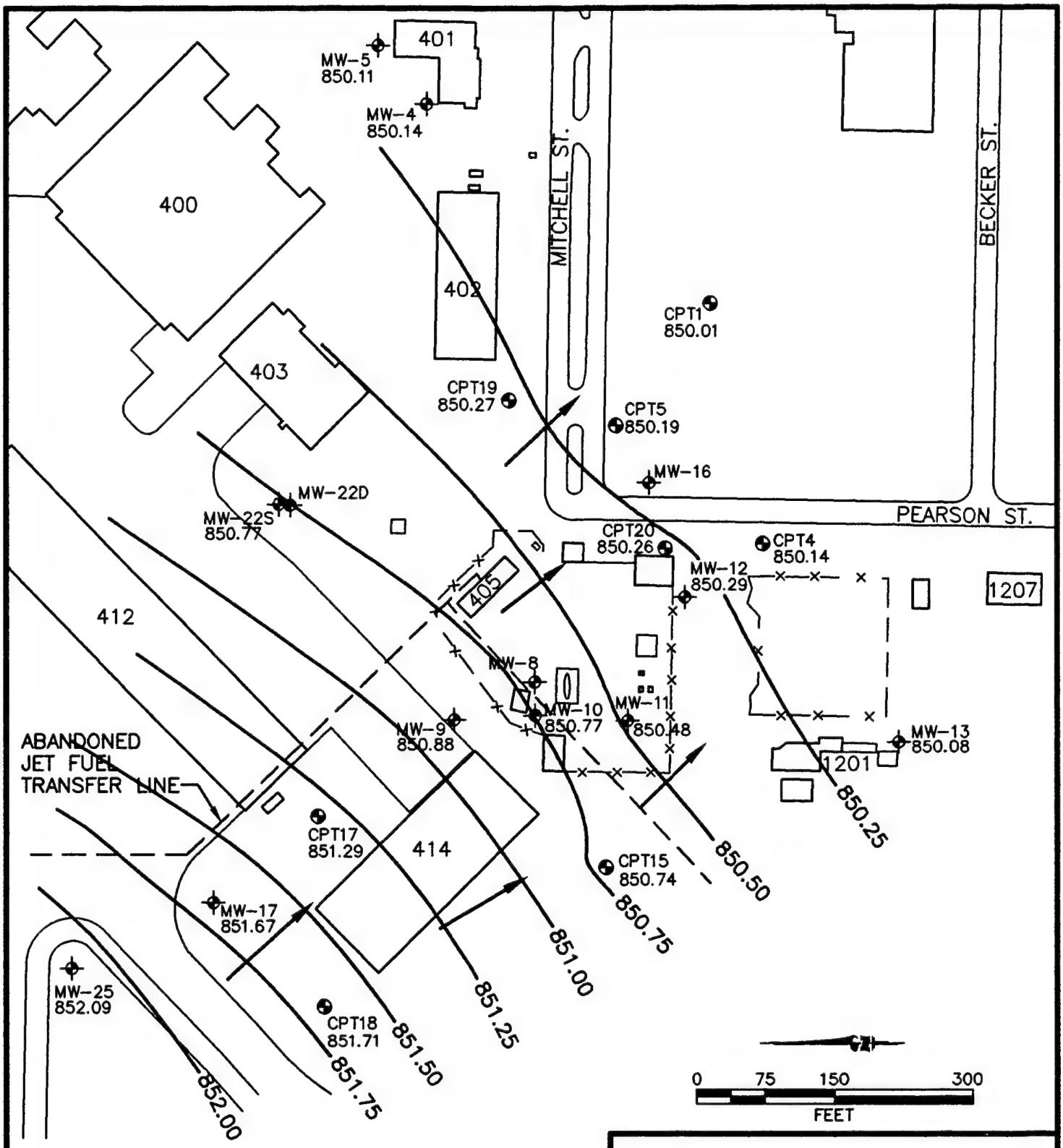
Ground water is present at depths of approximately 3 to 10 feet bgs. The water table is usually present in the sand unit, but locally is present in fill or in the fine-grained deposits. Historic ground water elevations generally indicate that flow is to the south-southeast; however, some past ground water surveys have produced contradictory results (ASI, 1991; Dames & Moore, 1992a). Ground water elevations measured in April 1991 indicated flow was to the south-southeast with a gradient of approximately 0.001 foot per foot (ft/ft) (ASI, 1991). Ground water elevation measurements were repeated in April and May of 1992; however, neither measurement round yielded a complete set of elevations. April 1992 elevations confirmed a south-southeast flow direction with a 0.001 ft/ft gradient over the southeastern portion of the Base. However, the May 1992 round indicated flow to both the northwest and southeast at gradients almost ten times those reported in previous rounds (Dames & Moore, 1992a). The May 1992 data set is suspect because it is incomplete and because other water level data suggest ground water flow is to the southeast.

On the basis of September 1994 ground water elevations, ground water flow at the site is to the southeast, with an average horizontal gradient of approximately 0.0022 ft/ft (Figure 3.4). Table 3.1 presents ground water elevation data collected in September 1994. Significant vertical flow gradients within the shallow aquifer are not apparent at this site. Vertical gradients (computed at four well nests) varied from -0.017 ft/ft (upward) to 0.027 ft/ft (downward). At one location the vertical gradient was 0.000 ft/ft (i.e., no measurable gradient), and at MW-22, the gradient was only 0.001 ft/ft (downward).

3.3.2.2 Hydraulic Conductivity

Several slug tests were performed in site monitoring wells by Dames & Moore (1992a). Results of these tests suggest that the uconsolidated deposits in this area have hydraulic conductivities ranging from 2×10^{-3} to 1.9×10^{-2} foot per minute (ft/min) [1×10^{-3} to 1×10^{-2} centimeter per second (cm/sec)].

Hydraulic conductivity was estimated at wells installed by Parsons ES using rising head and falling head slug tests as described in Section 2. Slug tests were performed in monitoring wells MW-13, MW-16, and MW-17. The results of these slug tests are summarized in Table 3.2. The



LEGEND

MW-4 850.14 — MONITORING WELL WITH WATER TABLE ELEVATION (FEET ABOVE MSL)

CPT1 850.01 — GROUND WATER MONITORING POINT WITH WATER TABLE ELEVATION (FEET ABOVE MSL)

—x—x—x— FENCE

—851.00— LINE OF EQUAL WATER TABLE ELEVATION (FEET ABOVE MSL) CONTOUR INTERVAL = 0.25 FEET

APPROXIMATE GROUND WATER FLOW DIRECTION

FIGURE 3.4

WATER TABLE ELEVATION MAP SEPTEMBER 1994

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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TABLE 3.1

WATER LEVEL ELEVATION DATA
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Location	Date	Datum [a] Elevation (ft msl) [b]	Ground Elevation (ft msl)	Total Depth (ft btoc) [c]	Depth to Water (ft btoc)	Water Elevation (ft msl)
MW-4	9/16/94	861.00	859.1	20.52	10.86	850.14
MW-5	9/16/94	860.82	858.87	23.23	10.71	850.11
MW-8	9/14/94	857.74	858.18	NA [d]	7.35	850.39
MW-9	9/16/94	858.46	856.43	NA	7.58	850.88
MW-10	9/16/94	859.05	857.13	17.32	8.28	850.77
MW-11	9/16/94	858.55	856.61	17.74	8.07	850.48
MW-12	9/16/94	858.91	856.96	16.98	8.62	850.29
MW-13	9/16/94	860.71	858.77	21.39	10.63	850.08
MW-16	9/16/94	858.38	858.61	16.52	8.46	849.92
MW-17	9/13/94	857.01	855.68	15.16	5.34	851.67
MW-22S	9/16/94	859.69	857.77	17.35	8.92	850.77
MW-22D	9/16/94	859.91	857.75	42.22	9.17	850.74
MW-25	9/16/94	858.61	856.35	16.7	6.52	852.09
CPT1S	9/16/94	861.05	861.25	10.58	-- [e]	--
CPT1D	9/16/94	861.05	861.23	20.52	11.04	850.01
CPT4S	9/16/94	858.11	858.23	8.18	7.97	850.14
CPT4D	9/16/94	858.11	858.25	18.15	7.97	850.14
CPT5S	9/16/94	858.47	858.67	10.07	8.28	850.19
CPT5D	9/16/94	858.61	858.45	20.24	8.24	850.37
CPT15 [f]	9/16/94	856.28	NA	9.02	5.54	850.74
CPT17S [f]	9/16/94	854.44	NA	6.12	3.15	851.29
CPT17D [f]	9/16/94	854.39	NA	16.04	3.40	850.99
CPT18	9/16/94	855.61	855.83	6.62	3.9	851.71
CPT19	9/16/94	858.75	858.93	10.88	8.48	850.27
CPT20	9/16/94	857.19	857.37	9.99	6.93	850.26

[a] Datum is top of PVC casing.

[b] ft msl = feet above mean sea level

[c] feet btoc = feet below top of casing

[d] NA = Data not available.

[e] -- = No water in monitoring point.

[f] Survey data for these wells are inaccurate; water levels are approximate.

average hydraulic conductivity of the sands in the shallow saturated zone as determined from these tests is 1.4×10^{-2} ft/min, or 6.9×10^{-3} cm/sec.

TABLE 3.2

SLUG TEST RESULTS
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

WELL	TEST	HYDRAULIC CONDUCTIVITY (ft/min)	HYDRAULIC CONDUCTIVITY (cm/sec)
MW-13	Rising Head	6.5×10^{-3}	3.3×10^{-3}
MW-13	Falling Head	2.1×10^{-2}	1.0×10^{-2}
MW-16	Rising Head	2.2×10^{-2}	1.1×10^{-2}
MW-16	Falling Head	8.4×10^{-3}	4.2×10^{-3}
MW-17	Rising Head	1.6×10^{-2}	8.0×10^{-3}
MW-17	Falling Head	8.3×10^{-3}	4.2×10^{-3}
	AVERAGE	1.4×10^{-2}	6.9×10^{-3}

3.3.2.3 Effective Porosity

Because of the difficulty involved in accurately determining effective porosity, accepted literature values for the type of soil comprising the shallow saturated zone were used. Freeze and Cherry (1979) give ranges of porosity for silt and sand of 0.25 to 0.50. The effective porosity for sediments of the shallow saturated zone is assumed to be 0.30.

3.3.2.4 Advective Ground Water Velocity

The advective velocity of ground water in the direction parallel to ground water flow is given by:

$$\bar{v} = \frac{K}{n_e}\frac{dH}{dL}$$

Where: $\bar{v}$ = Average advective ground water velocity (seepage velocity) [L/T]

K = Hydraulic conductivity [L/T] (1.4×10^{-2} ft/min)

dH/dL = Gradient [L/L] (0.0022 ft/ft)

n_e = Effective porosity (0.30).

Using this relationship in conjunction with site-specific data, the average advective ground water velocity at the site is 0.15 feet per day (ft/day), or approximately 54 feet per year.

3.3.2.5 Preferential Flow Paths

No preferential contaminant migration pathways were identified during the field work phase of this project. The relatively high hydraulic conductivity of the aquifer materials may prevent manmade features such as utility trenches or storm sewers from providing preferential flow paths. Except for fill in the excavation area south of Building 412, there is no indication of the presence of any high-conductivity zones of material that could influence subsurface flow.

3.3.3 Ground Water Use

Ground water from the shallow aquifer at Truax Field is not extracted for potable uses. The nearest potable supply wells are high-capacity wells at the Oscar Mayer processing plant, approximately 1.5 miles southwest of the site (ASI, 1991). These wells draw from the bedrock aquifer units.

SECTION 4

NATURE AND EXTENT OF CONTAMINATION AND SOIL AND GROUND WATER GEOCHEMISTRY

4.1 SOURCES OF CONTAMINATION

Sources of contamination present within the site include the former jet fuel transfer line and the POL yard. The former jet fuel transfer line is known to have released fuel into the subsurface near the southwestern end of Building 412. In fall 1993, 3,000 cubic yards of soil was excavated and, based on field gas chromatograph (GC) screening, contaminated soil was treated using low-temperature thermal desorption (Nine Springs, 1994). The extent of this excavation is indicated on Figure 1.2. Sampling of excavation sidewalls indicated that petroleum hydrocarbon contamination remained beneath Building 412 and the concrete aircraft ramps north and southeast of the excavation. Data from Dames & Moore (1992b) suggest that contamination extends a maximum of 50 feet to the northeast underneath Building 412 and to the southeast under the concrete apron southeast of the excavation.

Within the POL yard, only one spill has been documented, as noted in Section 1.2. In addition, tightness testing of the UST system suggested that the tanks are sound. ASI (1991) reported that field screening of soil samples collected in the vicinity of the POL yard indicated the presence of contamination, with the contaminated area centered just north of Building 405. However, no soil samples from this area were submitted for laboratory analysis.

In November 1994, another area of contaminated soil was discovered during excavation activities in the area between CPT15 and MW-9. A small amount of light nonaqueous-phase liquid (LNAPL) was observed to be floating on the surface of the ground water that had collected in the excavation. According to onsite observers, the LNAPL thickness was not measurable, but was "more than a sheen" (Lampe, 1994). In addition, the extent of the contaminated area appeared to be relatively limited. It is not

clear if this represents an additional source area or if it may be a result of LNAPL that has migrated from the POL yard or from the source area that was excavated in 1993.

4.2 SOIL CHEMISTRY

4.2.1 Residual Contamination

Residual LNAPL is defined as the LNAPL that is trapped in the aquifer by the processes of cohesion and capillarity, and therefore will not flow within the aquifer and will not flow from the aquifer matrix into a well under the influence of gravity. Mobile LNAPL is defined as LNAPL that is free to flow in the aquifer and that will flow from the aquifer matrix into a well under the influence of gravity. At this site, the LNAPL consists of fuel hydrocarbons, such as JP-4 fuel and, possibly, AVGAS.

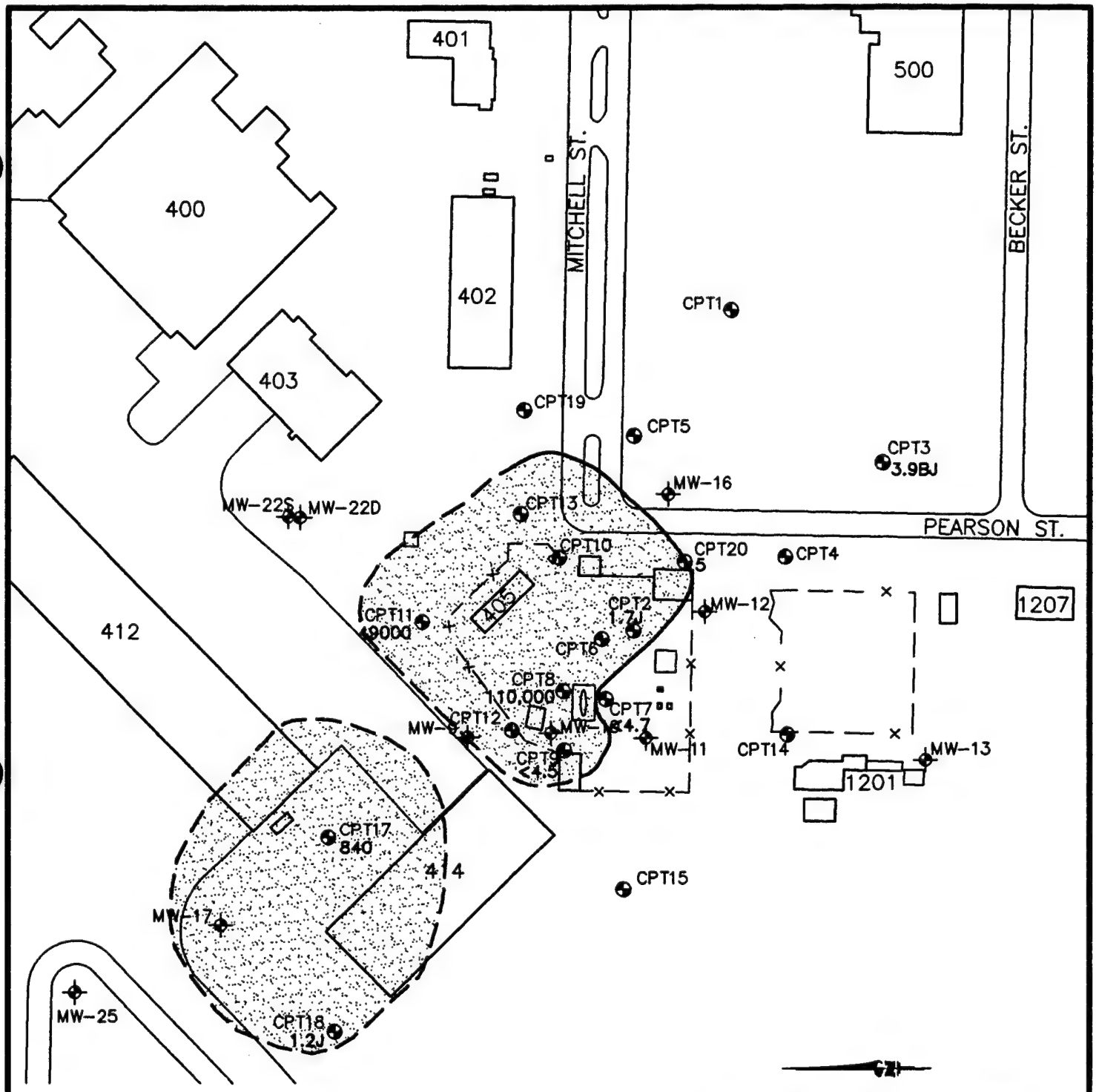
Previous evidence suggested that mobile LNAPL was present on the ground water and in the capillary fringe in the vicinity of monitoring well MW-8 (ASI, 1991). At that time, a nonmeasurable, green oily film was observed. A WDNR representative decided that the film did not indicate mobile LNAPL, so no sample was collected.

Mobile LNAPL was not detected in any of the wells in the site area during this investigation. Residual LNAPL contamination has been detected at the site and is described in the following sections.

4.2.1.1 LIF Data

LIF and analytical data collected during CPT activities suggest that petroleum hydrocarbons are present in soil in the areas indicated on Figure 4.1. LIF profiles collected at nearly all of the CPT locations within the shaded areas show significantly elevated fluorescence intensity, generally in the vicinity of the water table. In the vicinity of the POL yard, zones of elevated fluorescence range from 1 to 7 feet thick, with the thickest zones observed at CPT8 and CPT10, and the thinnest at CPT12 and CPT9. Notably, no hydrocarbons were detected by LIF at CPT7. At CPT20, the contaminated zone was 2.5 feet thick, but it was well above the water table.

South of Building 412, zones of elevated fluorescence intensity were observed at CPT16 and CPT17. At CPT16, the zone was 4.5 feet thick, while at CPT17, the zone



LEGEND

CPT1 1.4 — CPT LOCATION WITH LABORATORY TOTAL BTEX CONCENTRATION (μg/kg)

—x— FENCE

AREA OF SOIL CONTAMINATION INDICATED BY CPT/LIFDATA AND ANALYTICAL RESULTS (DASHED WHERE INFERRED)

NOTES: 1. "B" INDICATES THAT BTEX COMPOUNDS WERE DETECTED IN THE TRIP BLANK.

2. "J" INDICATES ESTIMATED VALUES.

FIGURE 4.1

SOIL HYDROCARBON CONTAMINATION AS INDICATED BY CPT/LIF AND LABORATORY ANALYTICAL RESULTS

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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was only 1.5 feet thick. However, that location was within the former excavation, where contaminated soil above the water table was excavated and treated. At CPT15, a contaminated zone 1 foot thick was observed, but this was from 1 foot bgs to 2 feet bgs. LIF profiles from locations outside the shaded area (i.e., CPT1, CPT3, CPT4, CPT5, CPT7, CPT14, and CPT19) did not indicate the presence of hydrocarbon contamination.

4.2.1.2 Soil BTEX Contamination

Soil samples from the vicinity of the water table were collected at nine locations and submitted for laboratory analysis of BTEX using US Environmental Protection Agency (EPA) Method SW8020. Table 4.1 presents laboratory soil BTEX data, and soil BTEX concentrations are presented on Figure 4.1. BTEX compounds were not detected at CPT11 and CPT7. BTEX compounds were generally detected within the area delineated by LIF data, except at CPT3, where the total BTEX concentration was 3.9J micrograms per kilogram (µg/kg). The "J" indicates that the concentration at this location is estimated because the compounds were detected at concentrations below their individual practical quantitation limits for each compound. In addition, three of the BTEX compounds were also present in the trip blank. Benzene was not detected at this location.

In the other samples where BTEX compounds were detected, total BTEX concentrations ranged from 1.2J µg/kg to 110,000 µg/kg. The highest concentrations were detected at CPT11 and CPT8, with total BTEX concentrations of 49,000 µg/kg and 110,000 µg/kg, respectively. Benzene concentrations at these two locations were 2,300 µg/kg and 760 µg/kg, respectively. Benzene was detected at only one other location (CPT17), where the benzene concentration was 140 µg/kg, and the total BTEX concentration was 840 µg/kg. In the remaining three samples (CPT2, CPT18, and CPT20), total BTEX concentrations ranged from 1.2J to 5 µg/kg.

4.2.1.3 Soil TPH Contamination

Total petroleum hydrocarbon (TPH) concentrations were quantified using modified versions of EPA Method 8015 (California Leaking Underground Fuel Tank Task Force, 1989). All samples were analyzed for total volatile hydrocarbons (TVH); and where sufficient soil was available, samples were collected for analysis of both TVH and total extractable hydrocarbons (TEH). Table 4.1 presents soil TPH data. TVH compounds were detected at CPT2, CPT8, CPT11, and CPT17, and ranged from 0.4 milligrams per

TABLE 4.1

FUEL HYDROCARBON COMPOUNDS DETECTED IN SOIL
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Sample Location	Sample Depth (feet bgs)	Benzene (µg/kg)	Toluene (µg/kg)	Ethylbenzene (µg/kg)	m&p-Xylene (µg/kg)	o-Xylene (µg/kg)	Total Xylenes (µg/kg)	Total BTEX (µg/kg)	Total Extractable Hydrocarbons (mg/kg)	Total Volatile Hydrocarbons (mg/kg)	Total Organic Carbon (%)
CPT2	7.0	<4.7	0.7 J[a/]	<4.7	0.6 J	0.4 J	1.0 J	1.7 J	NA[b/]	0.4	0.61
CPT3	5.0	<4.1	0.8 BJ[c/]	0.4 J	1.8 BJ	0.9 J	2.6 BJ	3.9 BJ	<10	<0.1	0.09
CPT7	7.8	<4.7	<4.7	<4.7	<4.7	<4.7	<4.7	<4.7	<12	<0.12	NA
CPT8	7.5	760	4,500 B	19,000	86,000	2,600	89,000	110,000	NA	3,000	NA
CPT9	5.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<11	<0.11	<0.06
CPT11	6.5	2,300	23,000	1,700	9,600	12,000	22,000	49,000	5,300	4,600	NA
CPT17	5.0	140	9.4 J	130	250	33	280	840	NA	17	NA
CPT18	4.5	<5.3	0.7 J	<5.3	0.5 J	<5.3	0.5 J	1.2 J	NA	<0.13	0.24
CPT20	6.8	<4.3	1.5 J	0.4 J	1.7 J	0.5 J	2.2 J	5	<11	<0.11	NA
CPT21[d/]	5.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<11	<0.11	NA

[a/] J = Estimated value.

[b/] NA = Not available.

[c/] B = Compound detected in method blank.

[d/] Duplicate of CPT9.

kilogram (mg/kg) at CPT2 to 4,600 mg/kg at CPT11. At CPT8, the TVH concentration was 3,000 mg/kg, and at CPT17 the TEH concentration was 17 mg/kg. TEH compounds were detected only in the sample from CPT11; however, TEH samples were not collected at CPT2, CPT8, and CPT17. At CPT11, the TEH concentration was 5,300 mg/kg.

4.2.2 Total Organic Carbon

TOC concentrations are used to estimate the amount of organic matter sorbed on soil particles or trapped in the interstitial passages of a soil matrix. The TOC concentration in the saturated zone is an important parameter used to estimate the amount of contaminant that could potentially be sorbed to the aquifer matrix. Sorption results in retardation of the contaminant plume migration relative to the average advective ground water velocity.

Samples for TOC analysis were collected in sandy material in the vicinity of the water table at CPT2, CPT3, CPT9, and CPT18. To avoid interference from carbon present in fuel hydrocarbons, these samples were collected from locations where LIF data indicated that little or no hydrocarbon contamination was present. The TOC content of the soil at these locations ranged from less than 0.06 percent to 0.61 percent (Table 4.1).

4.3 GROUND WATER CHEMISTRY

Three lines of evidence can be used to document the occurrence of natural attenuation: 1) geochemical evidence; 2) documented loss of contaminant mass at the field scale; and 3) laboratory microcosm studies. The first two lines of evidence (geochemical evidence and documented loss of contaminants) are used herein to support the occurrence of natural attenuation, as described in the following sections. Because these two lines of evidence strongly suggest that natural attenuation is occurring at this site, laboratory microcosm studies were not deemed necessary.

4.3.1 Dissolved Hydrocarbon Contamination

Laboratory analytical results for ground water samples collected during previous site investigations indicated the presence of fuel hydrocarbon contamination in the shallow saturated zone. Ground water samples collected in September 1994 by Parsons ES personnel confirmed these results. Table 4.2 summarizes ground water contaminant data for these samples.

TABLE 4.2

FUEL HYDROCARBON COMPOUNDS DETECTED IN GROUND WATER
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Well Location	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	m&p-Xylene (µg/L)	o-Xylene (µg/L)	Total Xylenes (µg/L)	Total BTEX (µg/L)	1,3,5-TMB (µg/L)	1,2,4-TMB (µg/L)	1,2,3-TMB (µg/L)	Total Hydrocarbons (TVH/TEH) (mg/L)
CPT1D	<0.4	0.7 B[a/]	<0.4	0.7 B	<0.4	0.7 B	1.4	<0.4	<0.4	<0.4	0.2/<0.5
CPT4D	5.2	0.7 B	0.9	1.8	0.4	2.2	9.0	0.4	1.6	0.6	<0.1/<0.5
CPT5S	<0.4	0.8 B	<0.4	0.5 B	<0.4	0.5 B	1.3	<0.4	<0.4	<0.4	0.3/<0.5
CPT5D	0.9	2.6 B	<0.4	1.2 B	<0.4	1.2 B	4.7	<0.4	0.6	<0.4	0.3/<0.5
CPT15S	14	<0.4	1.1	3.0	0.5	3.5	19	0.6	1.4	0.6	0.4/<0.5
CPT17S	26000	30 B	780	1130	420	1500	28000	84	350	230	25/ NA[b/]
CPT17D	3800	5.0 B	360	1000	10	1000	5200	140	570	360	13/3.3
CPT18S	83	0.4 B	3.3	9.8	1.2	11	98	1.6	4.6	1.7	0.6/NA
CPT19S	<0.4	0.6 B	0.7 B	2.5 B	1.8 B	4.3 B	5.6	3.3	7.7	2.1	0.2/<0.5
CPT20	<0.4	0.5 B	<0.4	1 B	0.5 B	1.5 B	2.0	0.7	2.4	0.5	<0.1/<0.5
HP-CPT3	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.1/<0.5
HP-CPT11	13	5.4 B	420	1670	49	1700	2100	270	720	340	14/3.7
MW-8	4700 E[c/]	15	220	1660	20	1700	6600	240	540	400	19/6.2
MW-9	98	1.2	0.7	0.9	1.7	2.6	100	6.4	14	1.8	0.6/0.5
MW-10	110	4.8	78	373	2.9	380	570	67	190	100	4.0/1.4
MW-11	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.1/<0.5
MW-12	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.1/<0.5
MW-13	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.1/<0.5
MW-16	5.1	<0.4	<0.4	2.2	<0.4	2.2	7.3	<0.4	2.4	<0.4	<0.1</0.5
MW-17	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	0.4	<0.1/<0.5
MW-22S	<0.4	0.4	<0.4	<0.4	<0.4	<0.4	0.4	0.6	0.6	0.6	0.5/<0.5
MW-25[d/]	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.1/<0.5
MW-26[e/]	89	1.0	0.6	1.7	1.3	3.0	94	6.7	15	1.7	<0.1/0.5
MW-25[f/]	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.1/<0.5

[a/] B = Compound detected in method blank.

[b/] NA=Not available.

[c/] E = Extrapolated value.

[d/] Duplicate sample collected from MW-11.

[e/] Duplicate sample collected from MW-9.

[f/] Sample collected from MW-25 (originally called MW-UNK).

4.3.1.1 Dissolved BTEX Contamination

Figure 4.2 is an isopleth map showing the distribution of total BTEX dissolved in ground water in September 1994. Where nested monitoring points or wells are present, isopleths are drawn using the maximum concentration detected at that location. The maximum observed total BTEX concentration was 28,000 micrograms per liter (µg/L), in the sample collected from CPT17S. At this location, the benzene concentration was 26,000 µg/L. In the sample collected from CPT17D, the total BTEX concentration was 5,200 µg/L, with a benzene concentration of 3,800 µg/L. Elsewhere, total BTEX concentrations ranged from 1.4 µg/L to 6,600 µg/L, with benzene concentrations from 0.9 µg/L to 4,700 µg/L. BTEX compounds were not detected at HP-CPT3, MW-11, MW-12, MW-13, MW-17, and MW-25 (Table 4.2).

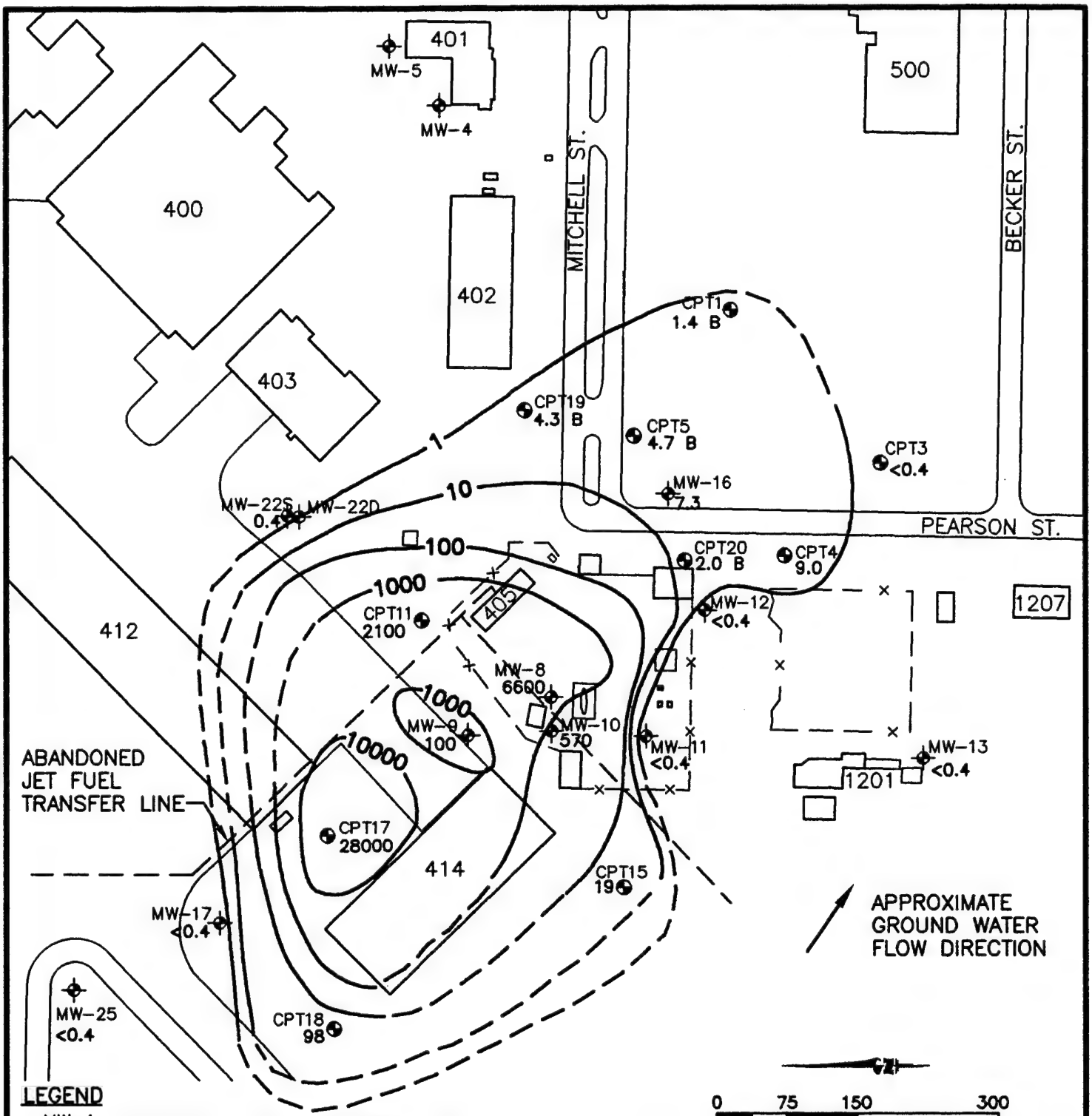
As indicated by the 1-µg/L isopleth, the BTEX plume is approximately 950 feet long and 600 feet wide, and is elongated parallel to the direction of ground water flow (Figure 4.2). The plume has a total area of at least 372,000 square feet (approximately 8.5 acres).

4.3.1.2 Dissolved TPH Contamination

Analytical results for TPH analyses are also presented in Table 4.2. Figure 4.3 is an isopleth map showing the distribution of TVH compounds in site ground water. The distribution of TVH compounds is similar to the distribution of BTEX compounds indicated on Figure 4.2. Dissolved TEH and/or TVH compounds were generally detected at locations where dissolved BTEX compounds also were detected. At no location were TPH compounds detected and BTEX compounds not detected. TVH concentrations ranged from 0.2 to 25 milligrams per liter (mg/L), and TEH concentrations ranged from 0.5 to 6.2 mg/L. TVH compounds were detected more frequently than TEH, and where both were detected, TVH concentrations were higher (Table 4.2).

4.3.2 Inorganic Chemistry and Geochemical Indicators of Biodegradation

Microorganisms obtain energy for cell production and maintenance by catalyzing the transfer of electrons from electron donors to electron acceptors. This results in the oxidation of the electron donor and the reduction of the electron acceptor. Electron donors at the site are natural organic carbon and fuel hydrocarbon compounds. Fuel



LEGEND

- MW-4 / 100 — MONITORING WELL LOCATION WITH TOTAL BTEX CONCENTRATION (µg/L)
- CPT1 / 1.4 — GROUND WATER MONITORING POINT WITH TOTAL BTEX CONCENTRATION (µg/L)
- —x— FENCE
- —100— LINE OF EQUAL BTEX CONCENTRATION (µg/L)(DASHED WHERE INFERRED)
  CONTOUR INTERVAL = VARIABLE

NOTES:

1. "B" INDICATES THAT BTEX COMPOUNDS WERE DETECTED IN THE TRIP BLANK.
2. WHERE DATA ARE AVAILABLE FROM DIFFERENT DEPTHS, THE HIGHEST BTEX CONCENTRATION WAS USED TO DRAW ISOPLETHS.

FIGURE 4.2

TOTAL BTEX ISOPLETHS FOR GROUND WATER SEPTEMBER 1994

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Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

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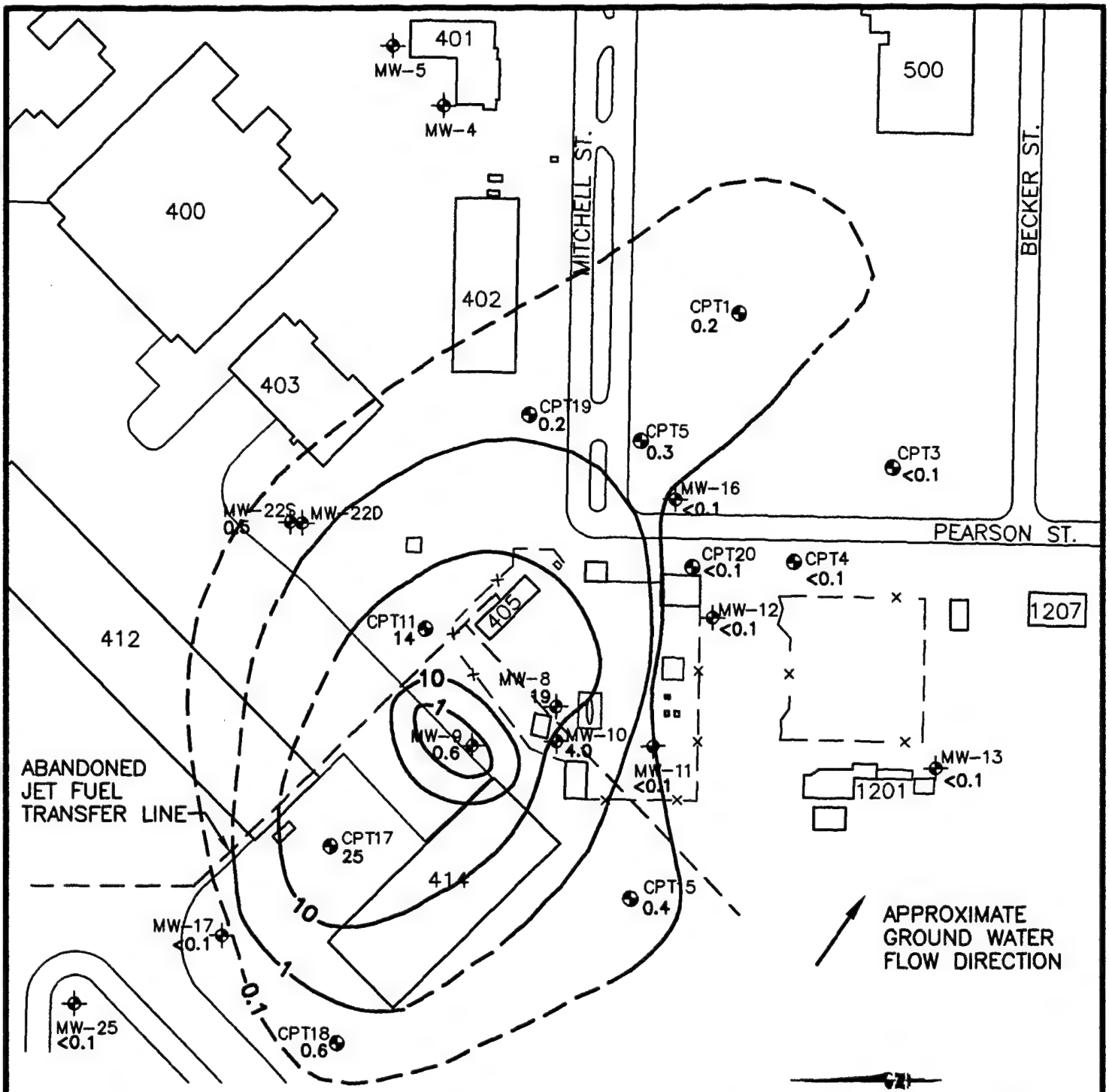

LEGEND

- MW-4 <0.1 — MONITORING WELL LOCATION WITH TOTAL VOLATILE HYDROCARBON CONCENTRATION (mg/L)
- CPT1 0.57 — GROUND WATER MONITORING POINT WITH TOTAL VOLATILE HYDROCARBON CONCENTRATION (mg/L)
- —x— FENCE
- —10— LINE OF EQUAL TOTAL VOLATILE HYDROCARBON CONCENTRATION (mg/L) (DASHED WHERE INFERRED)
- CONTOUR INTERVAL = VARIABLE

NOTE: WHERE DATA ARE AVAILABLE FROM DIFFERENT DEPTHS, THE CONCENTRATION FROM THE DEPTH CORRESPONDING TO THE HIGHEST BTEX CONCENTRATION WAS USED TO DRAW ISOPLETHS

FIGURE 4.3

TOTAL VOLATILE HYDROCARBON ISOPLETHS FOR GROUND WATER SEPTEMBER 1994

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Wisconsin Air National Guard at Truax Field
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hydrocarbons are completely degraded or detoxified if they are utilized as the primary electron donor for microbial metabolism (Bouwer, 1992). Electron acceptors are elements or compounds that occur in relatively oxidized states, and include oxygen, nitrate, ferrous iron, sulfate, and carbon dioxide. Microorganisms preferentially utilize electron acceptors while metabolizing fuel hydrocarbons (Bouwer, 1992). DO is utilized first as the prime electron acceptor. After the DO is consumed, anaerobic microorganisms typically use electron acceptors (as available) in the following order of preference: nitrate, ferric iron hydroxide, sulfate, and finally carbon dioxide.

Depending on the types and concentrations of electron acceptors present (e.g., nitrate, ferric iron, sulfate, carbon dioxide), pH conditions, and redox potential, anaerobic biodegradation can occur by denitrification, ferric iron reduction, sulfate reduction, or methanogenesis. Other, less common anaerobic degradation mechanisms such as manganese reduction may dominate if the physical and chemical conditions in the subsurface favor use of these electron acceptors. Anaerobic destruction of BTEX compounds is associated with the accumulation of fatty acids, production of methane, solubilization of iron, and reduction of nitrate and sulfate (Cozzarelli *et al.*, 1990; Wilson *et al.*, 1990). Environmental conditions and microbial competition will ultimately determine which processes will dominate. Vroblesky and Chapelle (1994) show that the dominant terminal electron accepting process can vary both temporally and spatially in an aquifer with fuel hydrocarbon contamination.

Site ground water data for electron acceptors such as nitrate and sulfate suggest that intrinsic remediation of hydrocarbons in the shallow aquifer by denitrification and sulfate reduction is occurring. In addition, data for ferrous iron (Fe^{2+}) and methane suggest that anaerobic degradation via ferric iron reduction and methanogenesis is occurring. Geochemical parameters for site ground water are discussed in the following sections.

4.3.2.1 Dissolved Oxygen

DO concentrations were measured at monitoring wells in September 1994. Table 4.3 summarizes DO concentrations. Figure 4.4 is an isopleth map showing the distribution of DO concentrations in ground water. Comparison of Figures 4.2 and 4.4 shows graphically that areas with elevated total BTEX concentrations correlate with areas with depleted DO concentrations. Within the BTEX plume area, DO concentrations are generally below 1 mg/L, and are as low as 0.14 mg/L (at MW-8). This is an indication

TABLE 4.3

GROUND WATER GEOCHEMICAL DATA
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Sample Location	Temperature (°C)	Dissolved Oxygen (mg/L)	Redox Potential (mV)	Total Alkalinity (mg/L)	pH	Chloride (mg/L)	Sulfate (lab) (mg/L)	Sulfate (field) (mg/L)	Sulfate (field dup[a/]) (mg/L)	Ferrous Iron (mg/L)	Total Iron (mg/L)	Nitrate (field) (mg/L)	Nitrate (field dup) (mg/L)	Nitrite (field) (mg/L)	Nitrite (field dup) (mg/L)	NO_2+NO_3 Nitrogen (mg/L)	Methane (mg/L)	Dissolved OC [b/] (mg/L)
CPT1D	15.4	0.48	-174	473	6.76	15.3	45.2	54.5	NA[c/]	0.57	0.63	0.0	NA	0.000	NA	0.790	<0.001	8.6
CPT4D	16.9	0.70	-142	415	6.67	4.99	7.94	5.7	NA	3.55	4.31	0.0	NA	0.000	0.000	0.370	0.76	NA
CPT5D	15.7	0.35	<-300	424	6.73	16.3	6.83	20.6	NA	10.1	21.8	0.0	0	0.000	NA	0.100	0.13	NA
CPT5S	19.8	0.57	-91	NA	6.72	16.9	5.01	2.60	NA	6.4	11.65	0.0	NA	0.000	NA	0.136	0.17	NA
CPT15S	20.4	0.24	-142	459	6.76	11.7	24.7	29.1	NA	0.32	0.59	0.2	NA	0.007	NA	0.100	0.01	NA
CPT17D	16.4	0.59	-135	251	NA	7.76	4.73	4.90	4.00	8.75	23.55	0.0	NA	0.000	NA	0.062	5.2	NA
CPT18S	22.8	1.15	90	NA	NA	1.95	113	77.5	94.5	0.14	0.38	0.0	NA	0.015	0.019	1.88	<0.001	NA
CPT19S	18.1	0.33	-174	450	6.64	30.1	25.3	40.8	NA	8.35	18.15	0.0	NA	0.000	NA	0.101	0.02	NA
CPT20S	16.8	1.45	41	378	6.69	1.85	17.0	10.6	NA	0.24	0.45	0.0	NA	0.006	NA	10.7	<0.001	NA
HP-CPT3	16.7	7.19	161	369	NA	3.63	29.0	30.2	NA	0.04	0.93	0.1	NA	0.005	NA	4.47	<0.001	2.5
HP-CPT11	16.2	0.42	-119.6	358	NA	6.22	2.85	6.10	NA	4.45	6.95	1.4	NA	0.001	NA	0.146	3.84	NA
MW-8	17.3	0.14	-83	565	NA	6.62	1.26	10.60	NA	15	27.3	0.0	NA	0.000	NA	<0.056	11.74	NA
MW-9	17.3	0.67	35	401	NA	26.0	20.0	26.2	NA	0.95	1.1	1.2	NA	0.01	NA	1.39	0.003	11.1
MW-10	17.0	0.34	-120	287	NA	4.95	1.56	3.2	3	11.3	24.75	0.3	0	0.000	0.000	<0.056	5.54	8.9
MW-11	18.0	0.61	270	292	8.39[d/]	3.97	33.1	37.8	NA	0.01	0.02	1.2	NA	0.014	NA	1.81	<0.001	NA
MW-11D[e/]	NA	NA	NA	294	NA	3.42	32.2	NA	NA	NA	NA	NA	NA	NA	NA	1.88	<0.001	NA
MW-12	16.9	0.63	250.1	270	7.43	12.6	17.7	25.7	NA	0.03	0.03	0.7	NA	0.013	NA	4.54	<0.001	NA
MW-13	16.6	4.02	264	333	7.09	3.43	9.11	17.3	14.9	0.02	0.03	0.8	0.7	0.019	0.024	3.43	<0.001	2.1
MW-16	19.9	0.38	-55	454	8.91[d/]	34.8	1.54	3.1	NA	4.55	22.7	1.9	NA	0.012	NA	<0.056	0.21	38
MW-17	16.9	0.60	246	281	7.4	3.19	15.2	13.5	NA	0.05	0.03	0.5	NA	0.024	NA	0.262	<0.001	NA
MW-22S	18.4	0.44	215.6	313	NA	33.6	38.5	44.2	NA	0.02	0.02	0.5	NA	0.007	NA	0.709	0.004	NA
MW-25	16.9	1.38	NA	347	NA	5.13	15.3	18.8	NA	0.31	0.45	0.5	NA	0.01	NA	0.449	<0.001	5.5

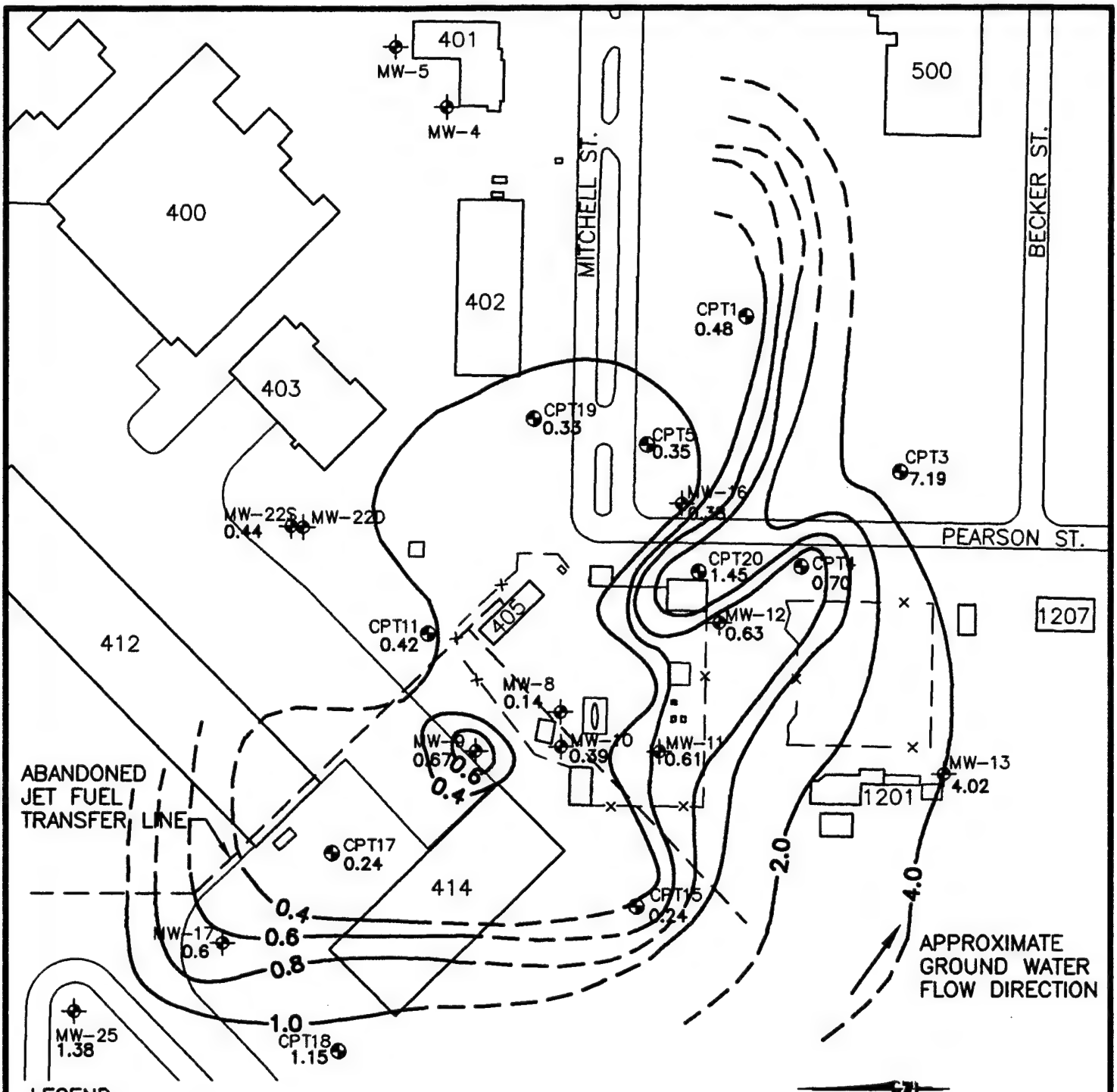
[a/] dup = duplicate

[b/] OC = organic carbon

[c/] NA = Not Analyzed.

[d/] Data suspect due to malfunctioning meter.

[e/] Duplicate of sample from MW-11



LEGEND

- MW-4 1.38 — MONITORING WELL LOCATION WITH DISSOLVED OXYGEN CONCENTRATION (mg/L)
- CPT1 0.48 — GROUND WATER MONITORING POINT WITH DISSOLVED OXYGEN CONCENTRATION (mg/L)
- —0.4— LINE OF EQUAL DISSOLVED OXYGEN CONCENTRATION (mg/L) (DASHED WHERE INFERRED)
- —x— FENCE

CONTOUR INTERVAL = VARIABLE

NOTE: WHERE DATA ARE AVAILABLE FROM DIFFERENT DEPTHS, THE CONCENTRATION FROM THE DEPTH CORRESPONDING TO THE HIGHEST BTEX CONCENTRATION WAS USED TO DRAW ISOPLETHS

FIGURE 4.4

DISSOLVED OXYGEN ISOPLETHS FOR GROUND WATER SEPTEMBER 1994

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that aerobic biodegradation of the BTEX compounds is occurring at the site. On the basis of the DO levels measured outside the plume (7.19 mg/L maximum, measured crossgradient from the plume at CPT3), it appears that DO is an important electron acceptor at this site.

The following equations describe the overall stoichiometry of aromatic hydrocarbon mineralization caused by aerobic microbial biodegradation. In the absence of microbial cell production, the oxidation (mineralization) of benzene to carbon dioxide and water is given by:

$$C_6H_6 + 7.5O_2 \rightarrow 6CO_2 + 3H_2O$$

Therefore, 7.5 moles of oxygen are required to metabolize 1 mole of benzene. On a mass basis, the ratio of oxygen to benzene is given by:

Benzene	6(12) + 6(1) = 78 gm
Oxygen	7.5(32) = 240 gm

Mass Ratio of Oxygen to Benzene = 240/78 = 3.08:1

Therefore, in the absence of microbial cell production, 3.08 mg of oxygen are required to completely metabolize 1 mg of benzene.

Similar calculations can be completed for toluene (3.13 oxygen to 1 toluene), ethylbenzene (3.17 oxygen to 1 ethylbenzene), and the xylenes (3.17 oxygen to 1 xylene). The average mass ratio of oxygen to total BTEX is thus 3.14:1. This means that approximately 0.32 mg of BTEX is mineralized for every 1.0 mg of DO consumed. With a maximum probable background DO concentration of approximately 7.19 mg/L and a minimum observed DO concentration of 0.14 mg/L, the shallow ground water at this site has the capacity to assimilate 2.3 mg/L (2,300 µg/L) of total BTEX through aerobic biodegradation. This is a conservative estimate of the assimilative capacity of DO because microbial cell mass production was not taken into account by the stoichiometry shown above.

When cell mass production is accounted for, the mineralization of benzene to carbon dioxide and water is given by:

$$C_6H_6 + 2.5O_2 + HCO_3 + NH_4 \rightarrow C_5H_7O_2N + 2CO_2 + 2H_2O$$

From this it can be seen that only 2.5 moles of DO are required to mineralize 1 mole of benzene when cell mass production is taken into account. On a mass basis, the ratio of DO to benzene is given by:

Benzene	6(12) + 6(1) = 78 gm
Oxygen	2.5(32)= 80 gm

Mass Ratio of Oxygen to Benzene = 80/78 = 1.03:1

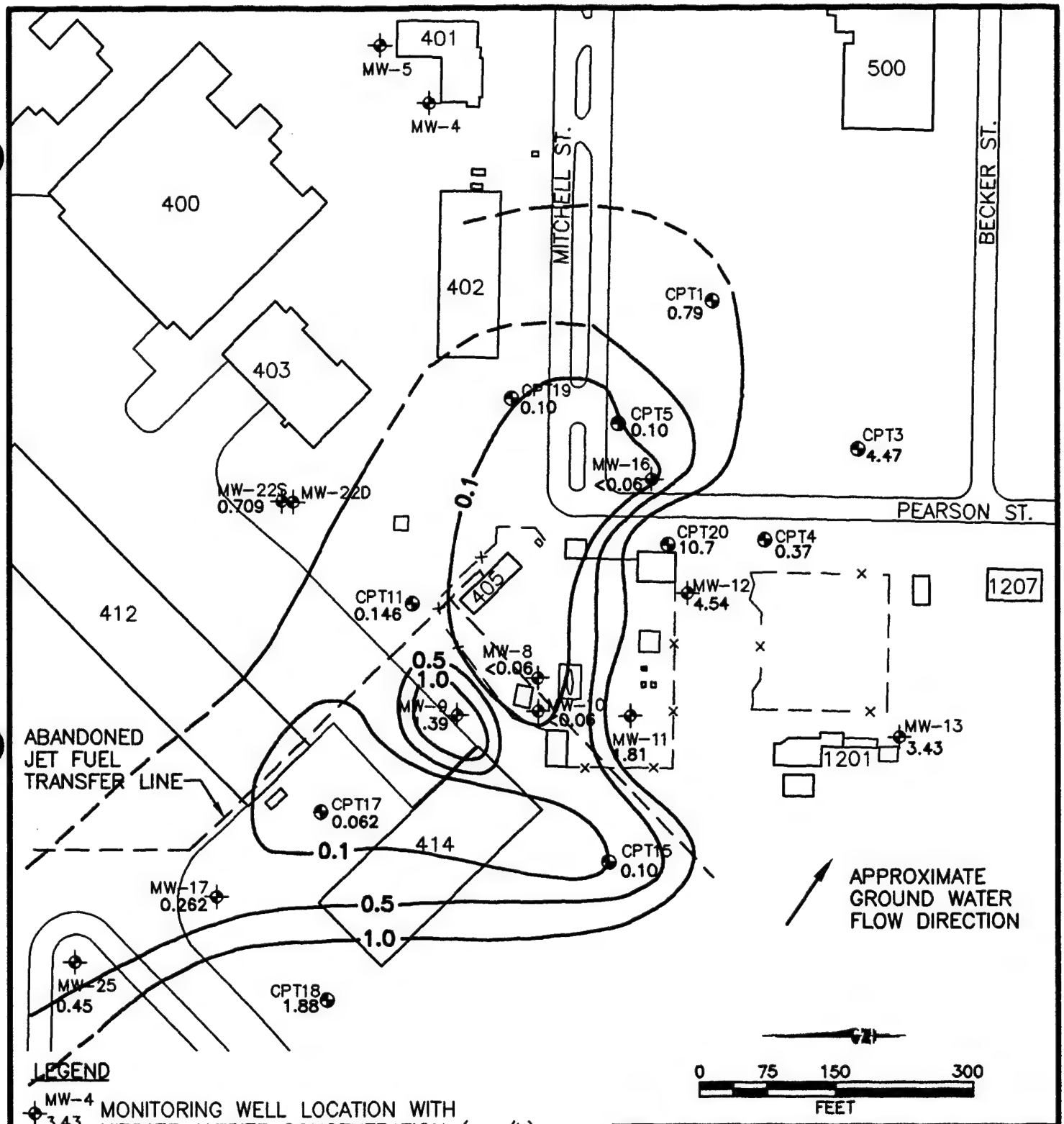
On the basis of these stoichiometric relationships, 1.03 mg of oxygen are required to mineralize 1 mg of benzene. Similar calculations can be made for toluene, ethylbenzene, and the xylenes. Based on these calculations, approximately 0.97 mg of BTEX is mineralized to carbon dioxide and water for every 1.0 mg of DO consumed. With a maximum background DO concentration of approximately 7.19 mg/L and a minimum DO concentration or 0.14 mg/L, the shallow ground water at this site has the capacity to assimilate 6.8 mg/L (6,800 μg/L) of total BTEX if microbial cell mass production is taken into account.

4.3.2.2 Nitrate/Nitrite

Concentrations of nitrate + nitrite [as nitrogen (N)] were measured at ground water monitoring wells in September 1994. Nitrate concentrations at the site range from <0.06 mg/L to 10.7 mg/L. Table 4.3 summarizes measured nitrate and nitrite (as N) concentrations. Figure 4.5 is an isopleth map showing the distribution of nitrate + nitrite (as N) in ground water in September 1994. Comparison of this figure with Figure 4.2 shows graphically that areas with elevated total BTEX concentrations have depleted nitrate + nitrite concentrations. Comparison of Figures 4.4 and 4.5 shows graphically that areas with depleted DO concentrations also have depleted nitrate + nitrite concentrations. These relationships provide strong evidence that anaerobic biodegradation of the BTEX compounds is occurring at the site through the microbially mediated process of denitrification.

In the absence of microbial cell production, the biodegradation of benzene via denitrification to carbon dioxide and water is given by:

$$6NO_3^- + 6H^+ + C_6H_6 \rightarrow 6CO_{2(g)} + 6H_2O + 3N_{2(g)}$$



LEGEND

- MW-4 3.43 — MONITORING WELL LOCATION WITH NITRATE+NITRITE CONCENTRATION (mg/L)
- CPT1 0.79 — GROUND WATER MONITORING POINT WITH NITRATE+NITRITE CONCENTRATION (mg/L)
- —x— FENCE
- —0.1— LINE OF EQUAL NITRATE CONCENTRATION (mg/L)(DASHED WHERE INFERRED)

CONTOUR INTERVAL = VARIABLE

NOTE: WHERE DATA ARE AVAILABLE FROM DIFFERENT DEPTHS, THE CONCENTRATION FROM THE DEPTH CORRESPONDING TO THE HIGHEST BTEX CONCENTRATION WAS USED TO DRAW ISOPLETHS.

FIGURE 4.5

NITRATE+NITRITE (AS N) ISOPLETHS FOR GROUND WATER SEPTEMBER 1994

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Based on this relationship, 6 moles of nitrate are required to mineralize 1 mole of benzene. On a mass basis, the ratio of nitrate to benzene is given by:

Benzene	6(12) + 6(1) = 78 gm
Nitrate	6(62) = 372 gm

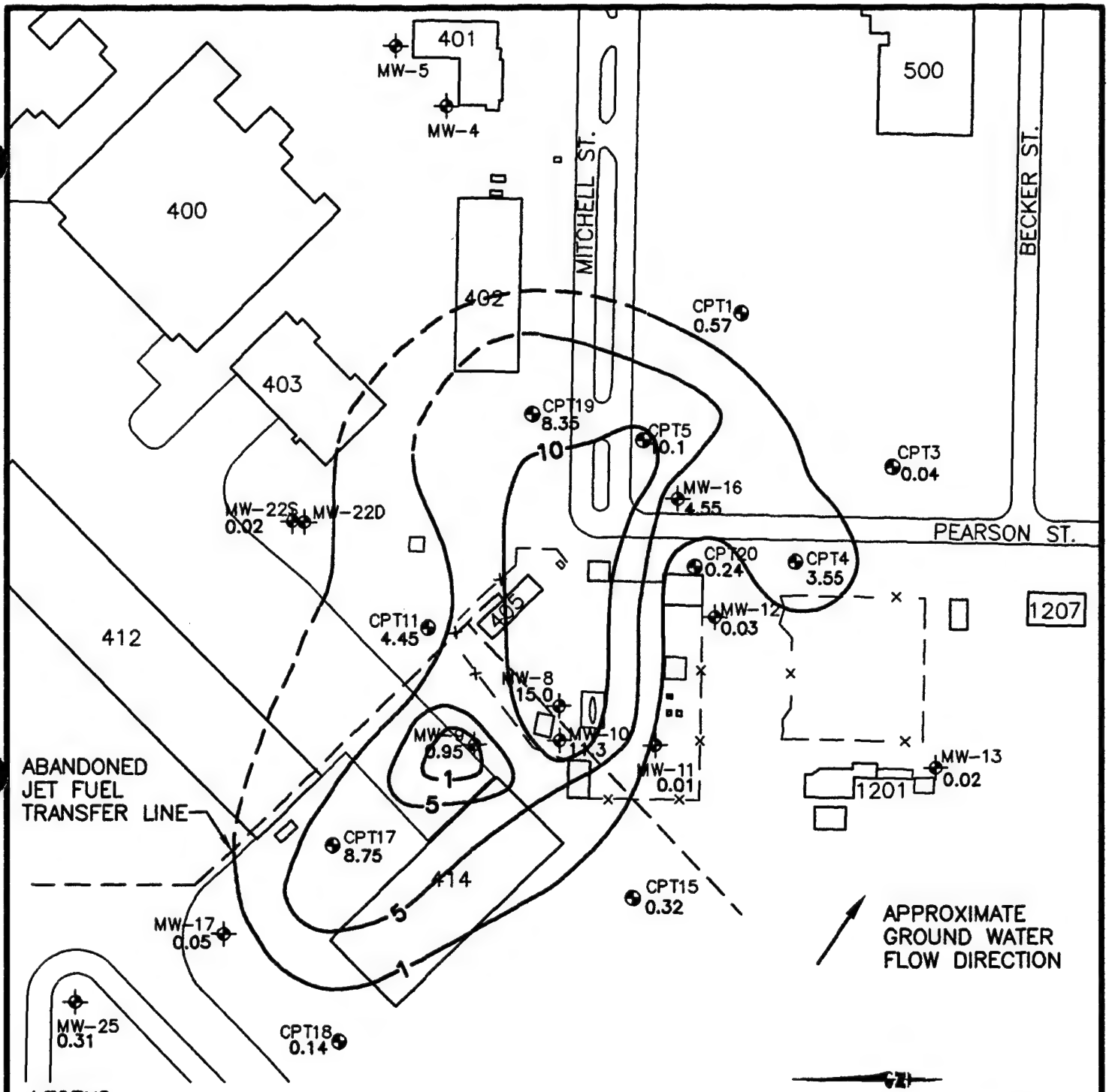
Mass ratio of nitrate to benzene = 372/78 = 4.77:1

In the absence of microbial cell production, 4.77 mg of nitrate are required to completely mineralize 1 mg of benzene. Similar calculations can be completed for toluene (4.85 mg nitrate to 1 mg toluene), ethylbenzene (4.92 mg nitrate to 1 mg ethylbenzene), and the xylenes (4.92 mg nitrate to 1 mg xylene). The average mass ratio of nitrate consumed to total BTEX degraded is 4.9:1. This means that approximately 0.20 mg of BTEX is mineralized for every 1.0 mg of nitrate consumed. With a maximum observed nitrate concentration of 10.7 mg/L, the shallow ground water at this site has the capacity to assimilate 2.1 mg/L (2,100 µg/L) of total BTEX during denitrification. This is a conservative estimate of the assimilative capacity of nitrate because microbial cell mass production has not been taken into account by the stoichiometry shown above (see Section 4.3.2.1).

4.3.2.3 Ferrous Iron

Ferrous iron (Fe^{2+}) concentrations were measured at ground water monitoring wells in June 1994. Table 4.3 summarizes ferrous iron concentrations. Figure 4.6 is an isopleth map showing the distribution of ferrous iron in ground water. Comparison of Figures 4.2 and 4.6 shows graphically that most of the area with elevated total BTEX concentrations has elevated ferrous iron concentrations. This suggests that ferric iron hydroxide (Fe^{3+}) is being reduced to ferrous iron during biodegradation of BTEX compounds. The highest measured ferrous iron concentration, 15 mg/L, was observed at MW-8, and the ferrous iron concentration measured at CPT17S was 8.75 mg/L. CPT17S and MW-8 are the locations with the two highest total BTEX concentrations. Background levels of ferrous iron are generally at or below 0.3 mg/L, as measured at wells with little or no BTEX contamination.

The following equations describe the overall stoichiometry of benzene oxidation by iron reduction caused by anaerobic microbial biodegradation. In the absence of microbial cell production, the mineralization of benzene is given by:



LEGEND

- MW-4 3.55 — MONITORING WELL LOCATION WITH FERROUS IRON CONCENTRATION (mg/L)
- CPT1 0.57 — GROUND WATER MONITORING POINT WITH FERROUS IRON CONCENTRATION (mg/L)
- —x— FENCE
- —5— LINE OF EQUAL FERROUS IRON CONCENTRATION (mg/L)(DASHED WHERE INFERRED)

CONTOUR INTERVAL = VARIABLE

NOTE: WHERE DATA ARE AVAILABLE FROM DIFFERENT DEPTHS, THE CONCENTRATION FROM THE DEPTH CORresponding TO THE HIGHEST BTEX CONCENTRATION WAS USED TO DRAW ISOPLETHS.

FIGURE 4.6

FERROUS IRON ISOPLETHS FOR GROUND WATER SEPTEMBER 1994

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$$60H^+ + 30Fe(OH)_{3,a} + C_6H_6 \rightarrow 6CO_2 + 30Fe^{2+} + 78H_2O$$

Therefore, 30 moles of ferric iron are required to metabolize 1 mole of benzene. On a mass basis, the ratio of ferric iron to benzene is given by:

Benzene	6(12) + 6(1) = 78 gm
Ferric Iron	30(106.85) = 3205.41 gm

Mass ratio of ferric iron to benzene = 3205.41/78 = 41.1:1

Therefore, in the absence of microbial cell production, 41.1 mg of ferric iron are required to completely metabolize 1 mg of benzene. Alternatively, the mass ratio of ferrous iron produced during respiration to benzene degraded can be calculated and is given by:

Benzene	6(12) + 6(1) = 78 gm
Ferrous Iron	30(55.85) = 1675.5 gm

Mass ratio of ferrous iron to benzene = 1675.5/78 = 21.5:1

Therefore, 21.5 mg of ferrous iron are produced during mineralization of 1 mg of benzene.

Similar calculations can be completed for toluene (21.86 mg of Fe^{2+} produced during mineralization of 1 mg of toluene), ethylbenzene (22 mg of Fe^{2+} produced during mineralization of 1 mg of ethylbenzene), and the xylenes (22 mg of Fe^{2+} produced during mineralization of 1 mg of xylene). The average mass ratio of Fe^{2+} produced during total BTEX mineralization is thus 21.8:1. This means that approximately 1 mg of BTEX is mineralized for every 21.8 mg of Fe^{2+} produced. The highest measured Fe^{2+} concentration was 15.0 mg/L. This suggests that the shallow ground water at this site has the capacity to assimilate 0.7 mg/L (700 µg/L) of total BTEX during iron reduction. This is a conservative estimate of the assimilative capacity of iron because microbial cell mass production has not been taken into account by the stoichiometry shown above (see Section 4.3.2.1). In addition, this calculation is based on observed ferrous iron concentrations and not on the amount of ferric hydroxide available in the aquifer. Therefore, iron assimilative capacity could be much higher.

Recent evidence suggests that the reduction of ferric iron to ferrous iron cannot proceed at all without microbial mediation (Lovley and Phillips, 1988; Lovley *et al.*, 1991; Chapelle, 1993). None of the common organic compounds found in low-

temperature, neutral, reducing ground water could reduce ferric oxyhydroxides to ferrous iron under sterile laboratory conditions (Lovley *et al.*, 1991). This means that the reduction of ferric iron requires microbial mediation by microorganisms with the appropriate enzymatic capabilities. Because the reduction of ferric iron cannot proceed without microbial intervention, the elevated concentrations of ferrous iron that were measured in the contaminated ground water at the site are very strong indicators of microbial activity.

4.3.2.4 Sulfate

Sulfate concentrations were measured at ground water monitoring wells in September 1994. Sulfate concentrations at the site range from 1.26 mg/L to 113 mg/L. Table 4.3 summarizes measured sulfate concentrations. Figure 4.7 is an isopleth map showing the distribution of sulfate in ground water in September 1994. Comparison of Figures 4.2 and 4.7 shows graphically that areas with elevated total BTEX concentrations have depleted sulfate concentrations. This is a strong indication that anaerobic biodegradation of BTEX compounds is occurring at the site through the microbially mediated process of sulfate reduction.

The following equations describe the overall stoichiometry of BTEX oxidation by sulfate reduction caused by anaerobic microbial biodegradation. In the absence of microbial cell production, the biodegradation of benzene is given by:

$$7.5H^+ + 3.75SO_4^{2-} + C_6H_6 \rightarrow 6CO_{2(g)} + 3.75H_2S^o + 3H_2O$$

Therefore, 3.75 moles of sulfate are required to mineralize 1 mole of benzene. On a mass basis, the ratio of sulfate to benzene is given by:

Benzene	6(12) + 6(1) = 78 gm
Sulfate	3.75(96) = 360 gm

Mass ratio of sulfate to benzene = 360/78 = 4.6:1

Therefore, in the absence of microbial cell production, 4.6 mg of sulfate are required to completely mineralize 1 mg of benzene. Similar calculations can be completed for toluene (4.7 mg sulfate to 1 mg toluene), ethylbenzene (4.75 mg sulfate to 1 mg ethylbenzene), and the xylenes (4.75 mg sulfate to 1 mg xylene). The average mass ratio of sulfate to total BTEX is thus 4.7:1. This means that approximately 0.21 mg of BTEX is mineralized for every 1.0 mg of sulfate consumed. Sulfate concentrations at nine

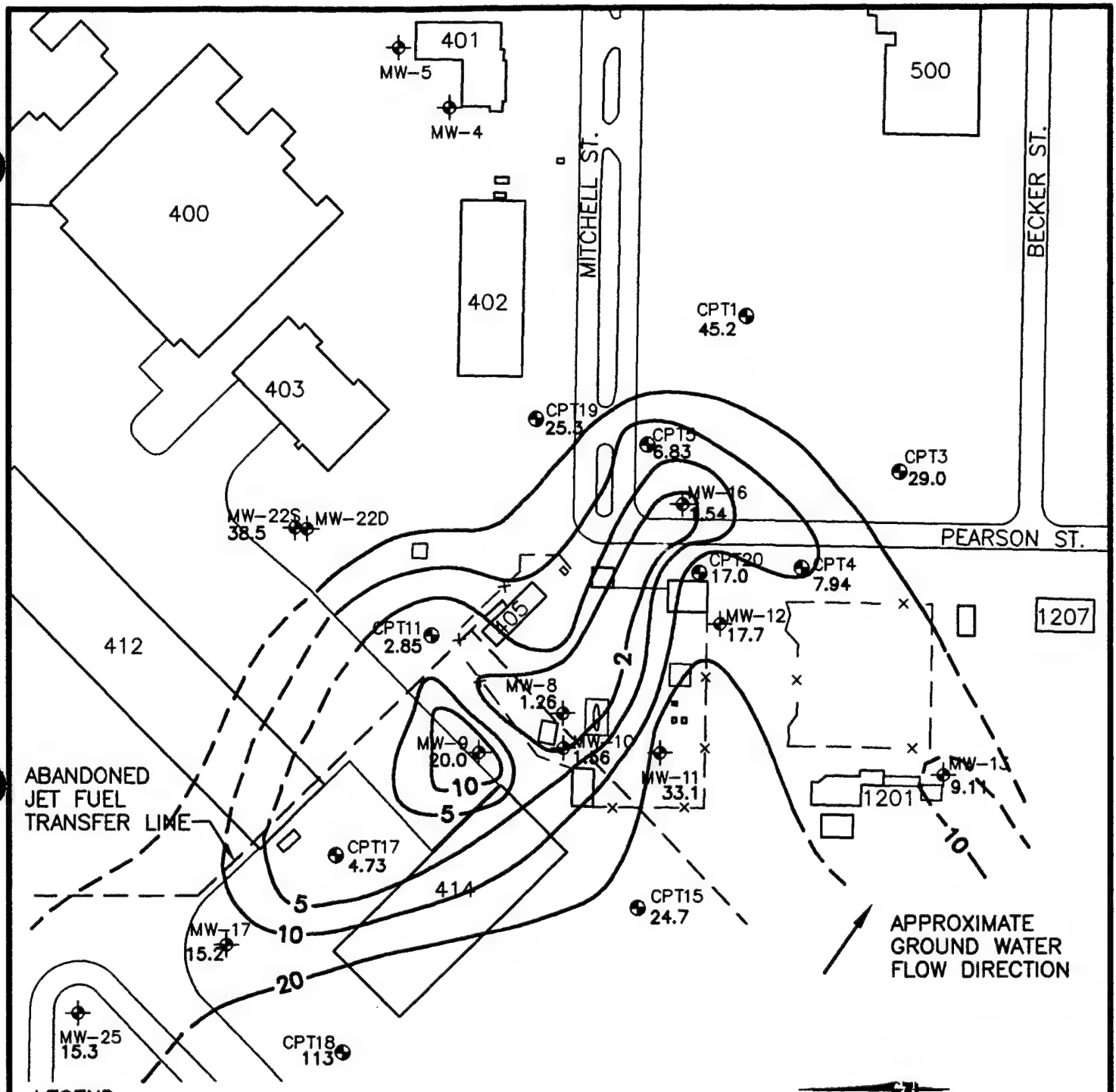

FIGURE 4.7

SULFATE ISOPLETHS FOR GROUND WATER SEPTEMBER 1994

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

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locations outside of the BTEX plume range from 9.1 mg/L to 113 mg/L, with six of the concentrations in the range between 24.7 and 45.2 mg/L. Assuming a background sulfate concentration of 25 mg/L, the shallow ground water at this site has the capacity to assimilate 5.25 mg/L (5,250 µg/L) of total BTEX during sulfate reduction. Again, this is a very conservative estimate of the assimilative capacity of sulfate because microbial cell mass production has not been taken into account by the stoichiometry shown above (see Section 4.3.2.1).

4.3.2.5 Methane in Ground Water

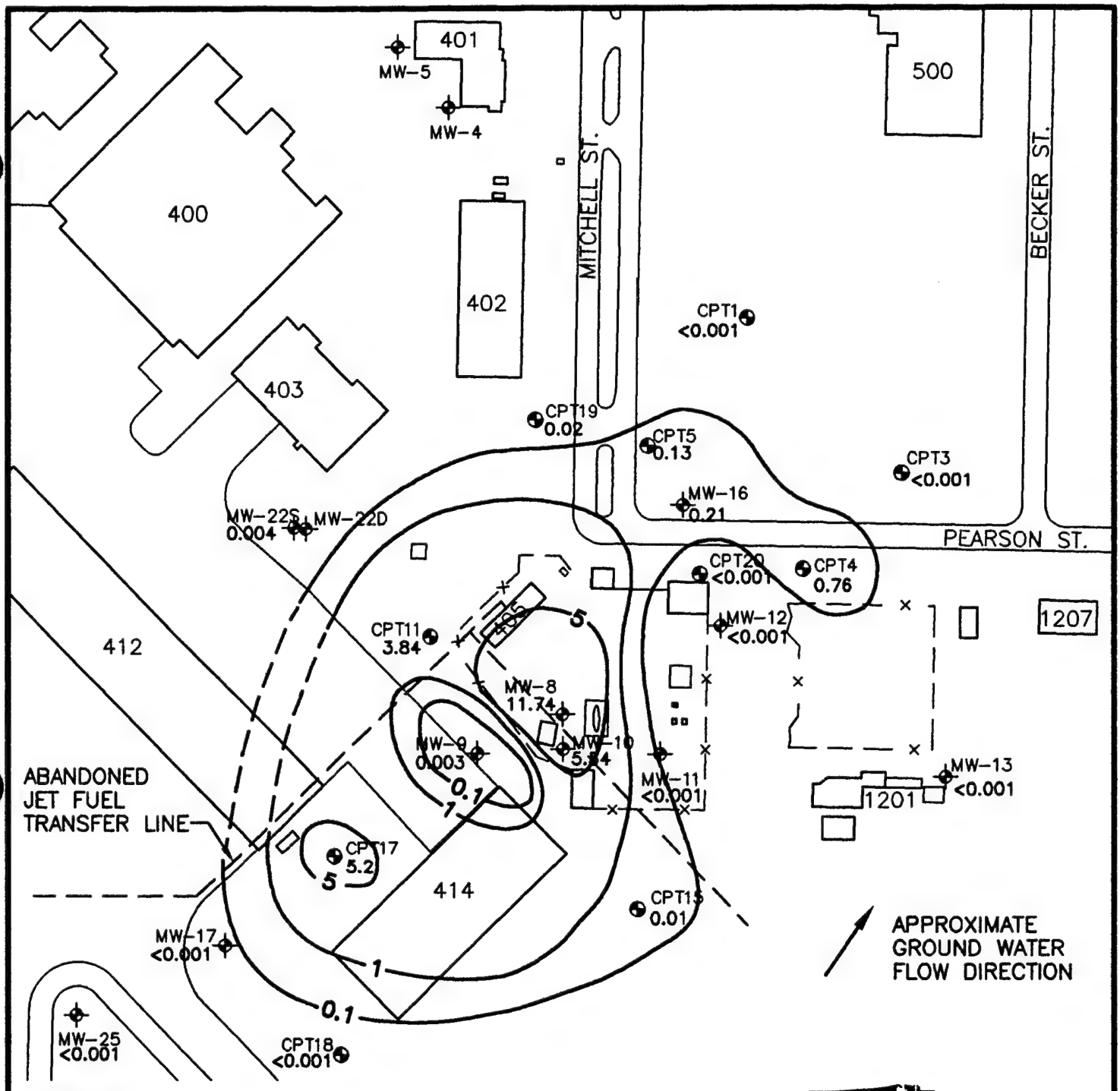
Methane concentrations were measured at ground water monitoring wells in September 1994. Table 4.3 summarizes methane concentrations. Figure 4.8 is an isopleth map showing the distribution of methane in ground water. Comparison of Figures 4.2 and 4.8 shows graphically that areas with elevated total BTEX concentrations correlate with elevated methane concentrations. This is a strong indication that anaerobic biodegradation of the BTEX compounds is occurring at the site. This is consistent with other electron acceptor data for this site, with the area having elevated methane concentrations corresponding with the areas with depleted DO, nitrate, and sulfate concentrations and elevated ferrous iron concentrations.

Methane concentrations ranged from <0.001 mg/L to 11.74 mg/L. Background levels of methane at wells outside areas with known BTEX contamination are below 0.01 mg/L. Samples collected from monitoring wells and monitoring points located near the areas with the highest BTEX concentrations contain the highest methane concentrations. In these locations, methane concentrations range from about 0.13 to 11.74 mg/L. The highest methane concentration observed at the site was in MW-8, with significantly elevated concentrations also present in CPT17, MW-10, and CPT11. Methane concentrations were also elevated at CPT5, MW-16, and CPT4.

The following equations describe the overall stoichiometry of benzene oxidation by methanogenesis. In the absence of microbial cell production, the mineralization of benzene is given by:

$$C_6H_6 + 4.5H_2O \rightarrow 2.25CO_2 + 3.75CH_4$$

The mass ratio of methane produced during respiration to benzene degraded can be calculated and is given by:



LEGEND

- MW-4 0.76 — MONITORING WELL LOCATION WITH METHANE CONCENTRATION (mg/L)
- CPT1 <0.001 — GROUND WATER MONITORING POINT WITH METHANE CONCENTRATION (mg/L)
- —x— FENCE
- —1— LINE OF EQUAL METHANE CONCENTRATION (mg/L)(DASHED WHERE INFERRED)

CONTOUR INTERVAL = VARIABLE

NOTE: WHERE DATA ARE AVAILABLE FROM DIFFERENT DEPTHS, THE CONCENTRATION FROM THE DEPTH CORRESPONDING TO THE HIGHEST BTEX CONCENTRATION WAS USED TO DRAW ISOPLETHS.

FIGURE 4.8

METHANE ISOPLETHS FOR GROUND WATER SEPTEMBER 1994

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Benzene	6(12) + 6(1) = 78 gm
Methane	3.75(16) = 60 gm

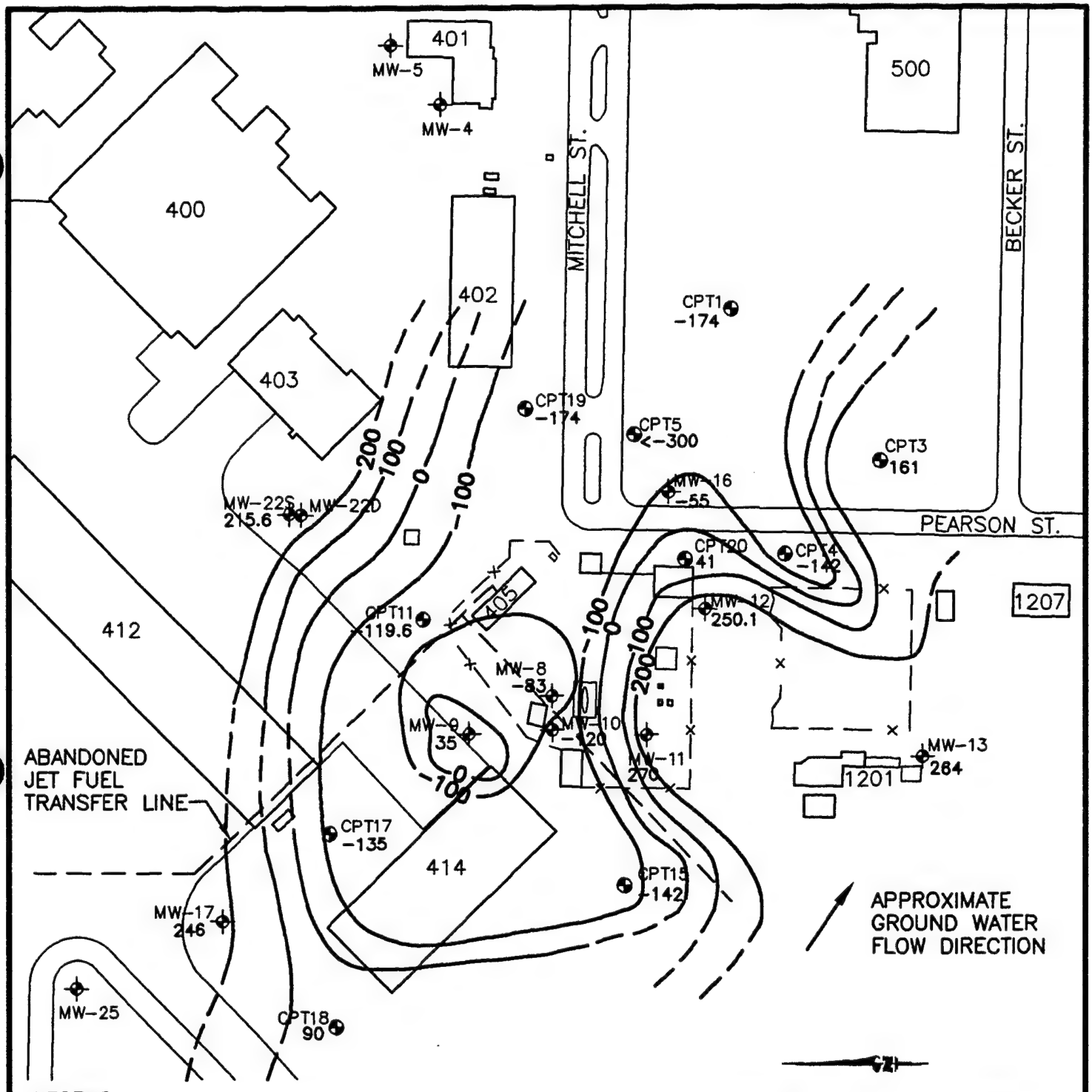
Mass ratio of methane to benzene = 60/78 = 0.77:1

Therefore, 0.77 mg of methane is produced during mineralization of 1 mg of benzene.

Similar calculations can be completed for toluene (0.78 mg of methane produced during mineralization of 1 mg of toluene), ethylbenzene (0.79 mg of methane produced during mineralization of 1 mg of ethylbenzene), and the xylenes (0.79 mg of methane produced during mineralization of 1 mg of xylene). The average mass ratio of methane produced during total BTEX mineralization is thus 0.78:1. This means that approximately 1 mg of BTEX is mineralized for every 0.78 mg of methane produced. The highest measured methane concentration was 11.74 mg/L. This suggests that the shallow ground water at this site has the capacity to assimilate up to 15.0 mg/L (15,000 µg/L) of total BTEX during methanogenesis. Again, this is a conservative estimate of the assimilative capacity of methanogenesis because microbial cell mass production is not taken into account by the stoichiometry shown above (see Section 4.3.2.1). In addition, these calculations are based on observed methane concentrations and not on the amount of carbon dioxide available in the aquifer. Therefore, methanogenic assimilative capacity could be much higher.

4.3.2.6 Reduction/Oxidation Potential

Redox potentials were measured at ground water monitoring wells in September 1994. Redox potential is a measure of the relative tendency of a solution to accept or transfer electrons. The redox potential of a ground water system depends on which electron acceptors are being reduced by microbes during BTEX oxidation. The redox potential at the site ranges from 264 millivolts (mV) to less than -300 mV. Table 4.3 summarizes available redox potential data. Figure 4.9 is a map that graphically illustrates the distribution of redox potentials. Redox potential is generally below -120 mV within the dissolved BTEX plume, except near MW-9, MW-8, and MW-16. As expected, areas at the site with low redox potentials appear to coincide with areas of high BTEX contamination; low DO, nitrate, and sulfate concentrations; and elevated ferrous iron and methane concentrations (compare Figure 4.9 with Figures 4.2, 4.4, 4.5, 4.6, 4.7, and 4.8).



LEGEND

- MW-4 -142 — MONITORING WELL LOCATION WITH REDOX POTENTIAL (mV)
- CPT1 -174 — GROUND WATER MONITORING POINT WITH REDOX POTENTIAL (mV)
- —x— FENCE
- -100- LINE OF EQUAL REDOX POTENTIAL (mV)(DASHED WHERE INFERRED)
- CONTOUR INTERVAL = 100 mV

NOTE: WHERE DATA ARE AVAILABLE FROM DIFFERENT DEPTHS, THE CONCENTRATION FROM THE DEPTH CORRESPONDING TO THE HIGHEST BTEX CONCENTRATION WAS USED TO DRAW ISOPLETH.

FIGURE 4.9

REDOX POTENTIAL MAP FOR GROUND WATER SEPTEMBER 1994

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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4.3.2.7 Alkalinity

Total alkalinity (as calcium carbonate) was measured at ground water monitoring wells in September 1994. These measurements are summarized in Table 4.3. Alkalinity is a measure of a ground water's ability to buffer changes in pH caused by the addition of biologically generated acids. Total alkalinity at the site is in the moderate range for ground water, varying from 251 mg/L at CPT-17D to 565 mg/L at MW-8. This amount of alkalinity should be sufficient to buffer potential changes in pH caused by biologically mediated BTEX oxidation reactions.

4.3.2.8 pH

pH was measured at ground water monitoring points and existing monitoring wells in September 1994. These measurements are summarized in Table 4.3. pH could not be measured at several locations due to a malfunction of the probe. The pH of a solution is the negative logarithm of the hydrogen ion concentration [H^+]. Ground water pH measured at the site ranges from 6.64 to 7.43. This range of pH is within the optimal range for BTEX-degrading microbes.

4.3.2.9 Temperature

Ground water temperature was measured at ground water monitoring points and existing monitoring wells in September 1994. Table 4.3 summarizes ground water temperature readings. Temperature affects the types and growth rates of bacteria that can be supported in the ground water environment, with higher temperatures generally resulting in higher growth rates. Temperatures in the shallow aquifer varied from 15.4 degrees Celsius (°C) to 22.8°C. These are moderate temperatures for shallow ground water, suggesting that bacterial growth rates should not be inhibited.

4.3.3 Discussion

Numerous laboratory and field studies have shown that hydrocarbon-degrading bacteria can participate in the degradation of many of the chemical components of jet fuel and gasoline, including the BTEX compounds (e.g., Jamison *et al.,* 1975; Atlas, 1981, 1984, 1988; Gibson and Subramanian, 1984; Reinhard *et al.,* 1984; Young, 1984; Bartha, 1986; Wilson *et al.,* 1986, 1987, and 1990; Barker *et al.,* 1987; Baedecker *et al.,* 1988;

Lee, 1988; Chiang *et al.,* 1989; Grbic-Galic, 1989 and 1990; Cozzarelli *et al.,* 1990; Leahy and Colewell, 1990; Altenschmidt and Fuchs, 1991; Alvarez and Vogel, 1991; Baedecker and Cozzarelli, 1991; Ball *et al.,* 1991; Bauman, 1991; Borden, 1991; Brown *et al.*, 1991; Edwards *et al.,* 1991 and 1992; Evans *et al.,* 1991a and 1991b; Haag *et al.,* 1991; Hutchins and Wilson, 1991; Hutchins *et al.,* 1991a and 1991b; Beller *et al.,* 1992; Bouwer, 1992; Edwards and Grbic-Galic, 1992; Edwards *et al.,* 1992; Thierrin *et al.,* 1992; Malone *et al.,* 1993; Davis *et al.,* 1994). Biodegradation of fuel hydrocarbons can occur when an indigenous population of hydrocarbon-degrading microorganisms is present in the aquifer and sufficient concentrations of electron acceptors and nutrients, including fuel hydrocarbons, are available to these organisms.

Comparison of BTEX, electron acceptor, and biodegradation byproduct isopleth maps for the Truax Field site provides strong qualitative evidence of biodegradation of BTEX compounds. Other observations and patterns in the data provide further evidence that biodegradation is reducing hydrocarbon concentrations at the site.

At several locations, dissolved benzene concentrations are high relative to the other BTEX compounds. For example, at CPT15S, CPT17D, CPT17S, CPT18, MW-8, MW-9, and MW-16, benzene concentrations make up 73 to 98 percent of the total BTEX concentrations at those locations. GC analyses of JP-4 and Jet-A fuels show that those petroleum mixtures contain 0.3 to 0.5 percent (by weight) benzene and between 2.9 and 4.4 percent total BTEX (IRP, 1987; Dunlap and Beckmann, 1988) Therefore, benzene originally makes up about 7 to 17 percent of the total BTEX concentration of these fuels. Benzene is more soluble than the other BTEX compounds, but it is only about three times more soluble than toluene (Verschueren, 1983), and it is more prone to volatilization. In general, benzene concentrations are much more than three times greater than toluene concentrations. Benzene is also more prone to volatilization, further mitigating the effects of its higher solubility. As a result, the apparent enrichment of dissolved benzene relative to toluene (as well as ethylbenzene and xylenes) in site ground water is another indicator of biodegradation, because benzene is typically more recalcitrant to biodegradation than toluene, ethylbenzene, and the xylene isomers (Barker *et al.*, 1987; Cozzarelli *et al.*, 1990).

In Figures 4.4 through 4.8, it can be seen that electron acceptor concentrations at MW-9 are elevated (and ferrous iron and methane concentrations depleted) relative to surrounding wells. Because this well is immediately downgradient of the source area that

was excavated in 1993, it would be expected that electron acceptor concentrations would be depleted due to biological activity in that area. However, MW-9 is located in a low grassy area that likely receives runoff from surrounding paved areas. This localized infiltration of fresh water likely replenishes electron acceptor concentrations in this area, producing elevated concentrations relative to adjacent wells.

Most importantly, the replenishment of electron acceptors in the vicinity of MW-9 has significantly reduced BTEX concentrations downgradient from the Building 412 source area (Figure 4.2). MW-9 is only about 185 feet downgradient of CPT17, and in that distance the total dissolved BTEX concentration decreases from 28,000 µg/L to 100 µg/L. Downgradient from MW-9, BTEX concentrations in the POL area are as high as 6,600 µg/L. These concentrations are elevated because the contaminated soil in the POL yard is acting as an additional source of dissolved BTEX. The contaminant mass loss between CPT17 and MW-9 is too great to be accounted for by sorption and dilution alone; biodegradation is the most plausible explanation for the observed decrease in BTEX concentrations.

This pattern can also be observed at MW-11, MW-12, and CPT20, along the southern margin of the POL yard. These sampling points are downgradient of contaminated areas, but are also in grassy areas that are surrounded by large paved or covered areas. At these wells, electron acceptor concentrations are slightly elevated, ferrous iron and methane concentrations are near background levels, and BTEX compounds are absent or present in very low concentrations. Nearly all of the isopleth maps show reentrants in that area, although the sulfate map shows a more subdued trend.

Because DO and other electron acceptor concentrations in these areas are being augmented, conditions that would otherwise be more favorable for processes such as methanogenesis or sulfate reduction locally become more favorable for aerobic respiration and denitrification. These conditions spur additional biodegradation, which consumes the new acceptors. As a result, the effects of the replenishment are slightly muted, particularly as indicated on the DO and nitrate + nitrite isopleth maps (Figures 4.4 and 4.5). At the same time, the processes of iron reduction, sulfate reduction, and methanogenesis become less important in those areas. Methane concentrations in the affected areas are below or just slightly above the detection limit, ferrous iron concentrations are below 0.2 mg/L, and sulfate concentrations are over 17 mg/L (Figures 4.6 through 4.8).

The low grassy areas that allow infiltration of precipitation are producing effects similar to those produced by infiltration galleries used as part of an active *in-situ* bioremediation program (for example, see Hutchins *et al.*, 1991c). This observable phenomenon is a further indication that biodegradation of petroleum hydrocarbons is occurring at this site. In addition, this evidence suggests that if the plume migrates further to the southeast, grassy areas present between the parking lots and streets west of Building 500 may also allow further replenishment of electron acceptors from infiltrating precipitation, stimulating biodegradation and possibly limiting plume migration.

4.3.4 Expressed Assimilative Capacity

The data presented in the preceding sections suggest that mineralization of BTEX compounds is occurring through the microbially mediated processes of aerobic respiration, denitrification, iron and sulfate reduction, and methanogenesis. Based on the stoichiometry presented in these sections, the expressed BTEX assimilative capacity of ground water at the Truax Field site is at least 25,350 µg/L (Table 4.4). The highest dissolved total BTEX concentration observed at the site was 28,000 µg/L, at CPT-17S.

Although the maximum observed BTEX concentration is greater than the calculated assimilative capacity, ground water at the site appears to have sufficient assimilative capacity to degrade the observed dissolved BTEX and limit plume migration. The calculations presented in the earlier sections are conservative because they do not account for microbial cell mass production, and the measured concentrations of ferrous iron and methane may not be the maximum achievable. In addition, there are additional influxes of water in the grassy areas, as discussed in Section 4.3.3. The addition of this water will locally increase the availability of electron acceptors, further increasing the assimilative capacity of the ground water at this site.

TABLE 4.4
EXPRESSED ASSIMILATIVE CAPACITY OF SITE GROUND WATER
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Electron Acceptor or Process	Expressed BTEX Assimilative Capacity (µg/L)
Dissolved Oxygen	2,300
Nitrate	2,100
Iron Reduction	700
Sulfate	5,250
Methanogenesis	15,000
Expressed Assimilative Capacity	25,350
Highest Observed Total BTEX Concentration	28,000

SECTION 5

GROUND WATER MODELING

5.1 GENERAL OVERVIEW AND MODEL DESCRIPTION

In order to help estimate degradation rates for dissolved-phase BTEX compounds at the Truax Field site and to help predict the future migration of these compounds, Parsons ES modeled the fate and transport of the dissolved BTEX plume. The modeling effort had three primary objectives: 1) to predict the future extent and concentration of the dissolved contaminant plume by modeling the combined effects of advection, dispersion, sorption, and biodegradation; 2) to assess the possible risk to potential downgradient receptors; and 3) to provide technical support for the natural attenuation remedial option at post-modeling regulatory negotiations. The model was developed using site-specific data and conservative assumptions about governing physical and chemical processes. Because of the conservative nature of model input, the reduction in contaminant mass caused by natural attenuation is expected to exceed model predictions. This analysis is not intended to represent a baseline assessment of potential risks posed by site contamination.

The Bioplume II code was used to estimate the potential for dissolved BTEX migration and degradation by naturally occurring mechanisms operating at the site. The Bioplume II model incorporates advection, dispersion, sorption, and biodegradation to simulate contaminant plume migration and degradation. The model is based upon the USGS Method of Characteristics (MOC) two-dimensional (2-D) solute transport model of Konikow and Bredehoeft (1978). The model was modified by researchers at Rice University to include a biodegradation component that is activated by a superimposed DO plume. Based on the work of Borden and Bedient (1986), the model assumes a reaction between DO and BTEX that is instantaneous relative to the advective ground water velocity. Bioplume II solves the USGS 2-D solute transport equation twice, once for hydrocarbon concentrations in the aquifer and once for a DO plume. The two plumes are combined using superposition at every particle move to simulate the instantaneous, biologically mediated, reaction between hydrocarbons and oxygen.

In recent years it has become apparent that anaerobic processes such as denitrification, iron reduction, sulfate reduction, and methanogenesis can be important BTEX degradation mechanisms (Grbic′-Galic′, 1990; Beller *et al.*, 1992; Edwards *et al.*, 1992; Edwards and Grbic′-Galic′, 1992, Grbic′-Galic′ and Vogel, 1987; Lovely *et al.*, 1989; Hutchins, 1991). Because there is evidence that anaerobic biodegradation processes are occurring at the site, these processes were accounted for during Bioplume II modeling using a first order anaerobic decay coefficient. The following subsections discuss in more detail the model setup, input parameters and assumptions, model calibration, and simulation results.

5.2 CONCEPTUAL MODEL DESIGN AND ASSUMPTIONS

Prior to developing a ground water model, it is important to determine if sufficient data are available to provide a reasonable estimate of aquifer conditions. In addition, it is important to ensure that any limiting assumptions can be justified. The most important assumption made when using the Bioplume II model is that oxygen-limited biodegradation is occurring at the site. The Bioplume II model assumes that the limiting factors for biodegradation are: 1) the presence of an indigenous hydrocarbon degrading microbial population, and 2) sufficient background electron acceptor concentrations. Data and information presented in Sections 3 and 4 suggest that oxygen, nitrate, ferric hydroxide, sulfate, and carbon dioxide (methanogenesis) are being used as electron acceptors for aerobic and anaerobic biodegradation. To be conservative, only oxygen was used as an electron acceptor in the Bioplume II model presented herein. Anaerobic biodegradation of petroleum hydrocarbons was simulated using a decay constant. Selection of this constant is discussed in Section 5.3.5.

On the basis of the data presented in Section 3, the shallow saturated zone was conceptualized and modeled as a shallow unconfined aquifer composed of fine- to medium-grained sand (Figures 3.2 and 3.3). The use of a 2-D model is appropriate at this site because the saturated interval is relatively homogenous, and water level data indicate that the local ground water flow system does not have a significant vertical component. Available evidence suggests that mobile LNAPL is not present at the site, but this evidence is inconclusive. Some of the contaminated soils at the site have been remediated, but continuing sources of dissolved BTEX contamination remain in the vicinity of Building 412 and in the vicinity of the POL yard.

5.3 INITIAL MODEL SETUP

Where possible, the initial setup for this model was based on existing site data. Where site-specific data were not available (e.g., for effective porosity), reasonable assumptions for the types of materials comprising the shallow aquifer were made based on widely accepted literature values. The following sections describe the basic model setup. Those Bioplume II model parameters that were varied during model calibration are discussed in Section 5.4.

5.3.1 Grid Design and Boundary Conditions

The maximum grid size for the Bioplume II model is limited to 20 columns by 30 rows. The dimension of each column and row can range from 0.1 to 999.9 feet. A 20- by 30-cell grid was used to model the Truax site. Each grid cell was 65 feet long by 50 feet wide. The grid was oriented so that the longest dimension was parallel to the overall direction of ground water flow. The model grid covers an area of 1.95 million square feet, or approximately 44.8 acres. The full extent of the model grid is indicated on Figure 5.1.

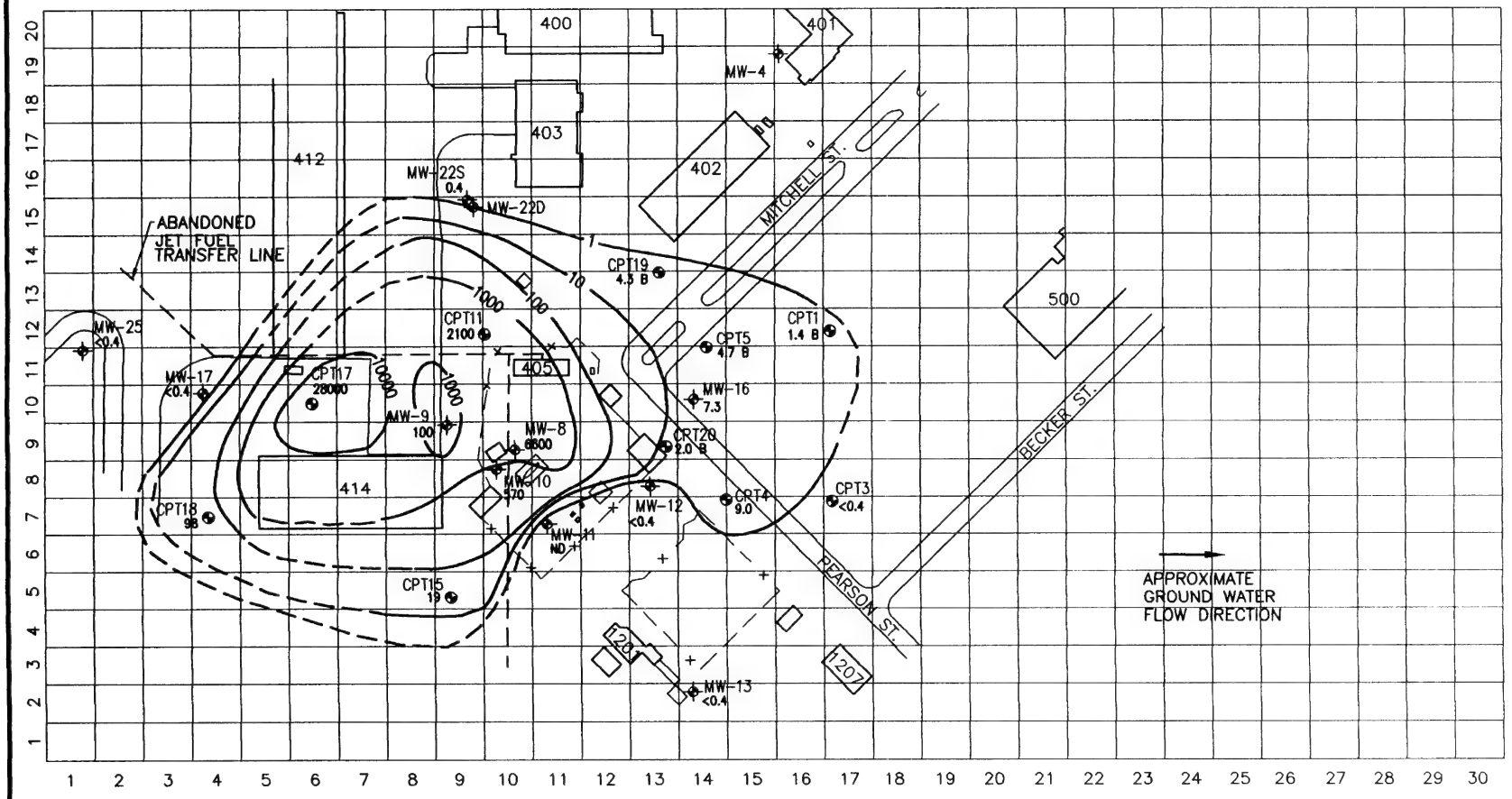
Model boundaries are mathematical statements that represent hydrogeologic boundaries, such as areas of specified head (e.g., surface water bodies or contour lines of constant hydraulic head) or specified flux. Hydrogeologic boundaries are represented by three mathematical statements that describe the hydraulic head at the model boundaries. These include:

- Specified-head boundaries (Dirichlet condition) for which the head is determined as a function of location and time only. Surface water bodies exhibit constant head conditions. Specified-head boundaries are expressed mathematically as:

$$Head = f(x, y, z, t)$$

  where f is the function symbol, x, y, and z are position coordinates, and t is time.

- Specified-flow boundaries (Neumann conditions), for which the mathematical description of the flux across the boundary is given. The flux is defined as a volumetric flow rate per unit area (e.g., $ft^3/ft^2/day$). No-flow boundaries are a special type of specified flow boundary and are set by specifying the flux to be zero. Examples of no-flow boundaries include ground water divides and



0 150 300
FEET

LEGEND

- MW-4 / 100 — MONITORING WELL LOCATION, TOTAL BTEX CONCENTRATION (µg/L)
- CPT1 / 1.4 — GROUND WATER MONITORING POINT, TOTAL BTEX CONCENTRATION (µg/L)
- —x— FENCE
- 402 — BUILDING
- —100— LINE OF EQUAL BTEX CONCENTRATION (µg/L)(DASHED WHERE INFERRED)
- CONTOUR INTERVAL = VARIABLE
- ND — NOT DETECTED

NOTE: "B" INDICATES THAT BTEX COMPOUNDS WERE DETECTED IN THE TRIP BLANK.

FIGURE 5.1

MODEL GRID

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impermeable hydrostratigraphic units. Specified-flux boundaries are expressed mathematically as:

$$Flux = f(x, y, z, t)$$

- 3) Head-dependent flow boundaries (Cauchy or mixed boundary conditions) where the flux across the boundary is calculated from a given boundary head value. This type of flow boundary is sometimes referred to as a mixed boundary condition because it is a combination of a specified-head boundary and a specified-flow boundary. Head-dependent flow boundaries are used to model leakage across semipermeable boundaries. Head-dependent flow boundaries are expressed mathematically as (Bear, 1979):

$$Flux = \frac{(H_0 - H)K'}{B'}$$

Where: H = Head in the zone being modeled (generally the zone containing the contaminant plume)
H_0 = Head in external zone (separated from plume by semipermeable layer)
K' = Hydraulic conductivity of semipermeable layer
B' = Thickness of semipermeable layer.

Natural hydraulic boundaries are modeled using a combination of the three types of model boundary conditions listed above. When possible, hydrologic boundaries such as surface water bodies, ground water divides, contour lines, or hydrologic barriers should coincide with the perimeter of the model. In areas lacking obvious hydrologic boundaries, specified-head or specified-flux boundaries can be specified at the model perimeter if the boundaries are far enough removed from the contaminant plume that transport calculations are not affected. Bioplume II requires the entire model domain to be bounded by zero-flux cells (also known as no-flow cells), with other boundary conditions established within the subdomain specified by the no-flow cells.

Specified-head boundaries for the model were set on the northwestern and southeastern perimeter of the model grid to simulate the southeasterly ground water flow observed at the site. Both boundaries were set in the approximate location of the water table indicated by water level data. The head of the northwestern boundary was estimated to be 851.8 to 852 feet above msl. The southeastern model boundary was defined by the assumed downgradient position of the 848.5-foot water table contour. The location of

this contour was estimated from available water table elevation and flow gradient data. These constant-head cells were placed far enough away from the BTEX plume to avoid potential boundary interferences.

The northeastern and southwestern model boundaries were configured as no-flow (specified flux) boundaries. In this case, the flux through these boundaries is assumed to be zero because flow is generally parallel to these boundaries. The base or lower boundary of the model is also assumed to be no-flow, and is assumed to be 20 feet below the water table. The upper model boundary is defined by the simulated water table surface.

5.3.2 Ground Water Elevation and Gradient

The water table elevation map presented in Figure 3.4 was used to define the starting heads input into the Bioplume II model. Ground water flow in the vicinity of the site is to the southeast with an average gradient of approximately 0.002 ft/ft. Data quantifying seasonal variations in ground water flow direction and gradient at the site are not available, but previous ground water flow data (ASI, 1991) and the BTEX and electron acceptor plume configurations are consistent with the observed ground water flow direction. As a result, it was assumed that the observed water levels were representative of steady-state conditions. As described in Section 5.4.1, the model was calibrated to the observed water table.

5.3.3 BTEX Concentrations

The total dissolved BTEX concentrations obtained from laboratory analytical results for each well location were used for model development. At nested monitoring points and well nests, the highest BTEX concentration observed at that location was used. Table 4.2 presents dissolved BTEX concentration data. Figure 4.2 shows the areal distribution of dissolved BTEX compounds in September 1994.

The BTEX plume observed in September 1994 covers an area of at least 372,000 square feet (8.5 acres). The shape and distribution of the total BTEX plume is the result of advective-dispersive transport and biodegradation of dissolved BTEX contamination.

As described in Section 5.4.2, the simulated BTEX plume was calibrated to match the observed BTEX plume.

5.3.4 Dissolved Oxygen

As discussed previously, the Bioplume II model assumes an instantaneous reaction between the BTEX plume and the DO plume. The discussion presented in Section 4 suggests that DO, nitrate, ferric iron, sulfate, and carbon dioxide (methanogenesis) are being used as electron acceptors for biodegradation of BTEX compounds at the site. To be conservative, the total BTEX plume at the site was modeled assuming that DO was the only electron acceptor being utilized at a rate that is instantaneous relative to the advective ground water flow velocity for the biodegradation of the BTEX compounds. As described in Section 5.3.5, anaerobic biodegradation, which is not instantaneous relative to the advective ground water velocity, was accounted for using a rate constant.

Ground water samples collected in uncontaminated portions of the aquifer suggest that background DO concentrations at the site are as high as 7.19 mg/L (observed at CPT-3). However, immediately upgradient of the plume (at MW-25), the DO concentration was only about 1.4 mg/L, and cross-gradient from the plume (at MW-13) the DO concentration was about 4.0 mg/L. Therefore, background oxygen levels were assumed to be 2 to 5 mg/L for Bioplume II model development. Table 4.3 contains DO data for the site. Figure 4.3 is a DO isopleth map. The initial model setup assumed that the DO distribution observed in September 1994 was a reasonable approximation of previous DO distributions (after contaminants were introduced to the shallow aquifer). Oxygen input data are included in Appendix C.

The upgradient constant-head cells in the Bioplume II model require background DO concentrations to be input as constant concentrations to simulate incoming electron acceptors. The background DO concentrations of 2 to 5 mg/L were used for these cells. Immediately upgradient of the plume, the DO concentrations were set at 2 mg/L, gradually increasing to 5 mg/L near the no-flow boundaries.

5.3.5 Anaerobic Degradation Rates

Available data strongly suggest that anaerobic degradation is occurring at the site. Although DO concentrations at the site are sufficient to support some aerobic

biodegradation of dissolved BTEX, combined anaerobic processes account for a much greater portion of the assimilative capacity of site ground water (Table 4.4). Anaerobic degradation must therefore be simulated with Bioplume II to make predictions are meaningful. The Bioplume II model simulates anaerobic biodegradation by assuming that such degradation follows first-order kinetics. As with a large number of biological processes, anaerobic biodegradation can generally be described using a first-order rate constant and the equation:

$$\frac{C}{C_0} = e^{-kt}$$

Where: C = Contaminant Concentration at Time t
C_0 = Initial Contaminant Concentration
k = Coefficient of Anaerobic Decay (anaerobic rate constant)
t = time

In order to calculate anaerobic rate constants, the apparent degradation rate must be normalized for the effects of dilution caused by advective-dispersive processes. This can be accomplished by normalizing the concentration of each contaminant to the concentration of a component of jet fuel (a tracer) that has similar sorptive properties but that is fairly recalcitrant. Observed BTEX concentration data can be normalized to 1,3,5-TMB, 1,2,4-TMB, and 1,2,3-TMB or another tracer with similar physiochemical properties. The TMB compounds can serve as good tracers because they can be recalcitrant under anaerobic conditions, and they have sorptive properties similar to the BTEX compounds (Cozzarelli *et al.*, 1990 and 1994).

Due to the site configuration, anaerobic rate constants could not be calculated based on BTEX and TMB data. Downgradient from the Building 412 source area, the concentrated influx of recharge has reduced hydrocarbon concentrations so much that no TMB compounds are present. In addition, TMB compounds were not detected downgradient of the POL yard. These conditions prevented normalization calculations. However, a review of recent literature indicates that anaerobic rate constants have been calculated at other sites. For example, Chapelle (1994) reported that at two different sites with anaerobic ground water conditions the anaerobic rate constants were both approximately 0.01 day^{-1}. Wilson *et al.* (1994), report first-order anaerobic biodegradation rates of 0.05 to 1.3 $week^{-1}$ (0.007 to 0.185 day^{-1}). Stauffer *et al.* (1994) report rate constants of 0.01 and 0.018 day^{-1} for benzene and p-xylene, respectively.

On the basis of the literature values [and previous experience], an anaerobic rate constant of 0.004 day^{-1} was used in the Bioplume II model. This value was selected because it is less than the values reported in the literature, and is therefore conservative.

5.4 MODEL CALIBRATION

Model calibration is an important component in the development of any numerical ground water model. Calibration of the flow model demonstrates that the model is capable of matching hydraulic conditions observed at the site; calibration of a contaminant transport model superimposed upon the calibrated flow model helps verify that contaminant loading and transport conditions are being appropriately simulated. The numerical flow model presented herein was calibrated by altering transmissivity in a trial-and-error fashion until simulated heads approximated observed field values within a prescribed accuracy. After calibration of the flow model, the numerical transport model was calibrated by altering hydraulic parameters and transport parameters in a trial-and-error fashion until the simulated BTEX plume approximated observed field values. Table 5.1 lists input parameters used for the modeling effort. Model input and output are included in Appendix D.

5.4.1 Water Table Calibration

The shallow water table at the Truax Field site was assumed to be influenced only by continuous recharge and discharge at the constant-head cells established at the upgradient and downgradient model boundaries. To be conservative, recharge of the aquifer through rainfall (which would add water, thereby increasing dilution of the plume) was not included in the model. This is a reasonable assumption because much of the model domain is covered by pavement or buildings, and the areas of recharge described Section 4.3.3 (e.g., in the vicinity of MW-9) are small relatively to the model area. Potential recharge by other sources was omitted because of a lack of reliable data. Only the initial water levels at the constant-head cells and the transmissivity values were varied to calibrate the water table surface. The model was calibrated under steady-state conditions.

TABLE 5.1

BIOPLUME II MODEL INPUT PARAMETERS
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

			Model Runs	
Parameter	Description	Calibrated Model Setup	MAD_B	MAD_C
NTIM	Maximum number of time steps in a pumping period	6	30	27
NPMP	Number of Pumping Periods	1	2	4
NX	Number of nodes in the X direction	20	20	20
NY	Number of nodes in the Y direction	30	30	30
NPMAX	Maximum number of Particles NPMAX=(NX-2)(NY-2)(NPTPND) + (Ns[a/])(NPTPND) + 250	5250	5250	5250
NPNT	Time step interval for printing data	1	1	1
NITP	Number of iteration parameters	7	7	7
NUMOBS	Number of observation points	0	0	0
ITMAX	Maximum allowable number of iterations in ADIP [b/]	200	200	200
NREC	Number of pumping or injection wells	0	0	0
NPTPND	Initial number of particles per node	9	9	9
NCODES	Number of node identification codes	6	6	6
NPNTMV	Particle movement interval (IMOV)	0	0	0
NPNTVL	Option for printing computed velocities	1	1	1
NPNTD	Option to print computed dispersion equation coefficients	0	0	0
NPDELC	Option to print computed changes in concentration	0	0	0
NPNCHV	Option to punch velocity data	0	0	0
NREACT	Option for biodegradation, retardation and decay	1	1	1
PINT	Pumping period (years)	3	3, 30	3, 1, 1, 27
TOL	Convergence criteria in ADIP	0.001	0.001	0.001
POROS	Effective porosity	0.30	0.30	0.30
BETA	Characteristic length (long. dispersivity; feet)	25	25	25
S	Storage Coefficient	0 (Steady-State)	0	0
TIMX	Time increment multiplier for transient flow	-	-	-
TINIT	Size of initial time step (seconds)	-	-	-
XDEL	Width of finite difference cell in the x direction (feet)	50	50	50
YDEL	Width of finite difference cell in the y direction (feet)	65	65	65
DLTRAT	Ratio of transverse to longitudinal dispersivity	0.25	0.25	0.25
CELDIS	Maximum cell distance per particle move	0.5	0.5	0.5
ANFCTR	Ratio of Tyy to Txx (1 = isotropic)	1	1	1
DK	Distribution coefficient	0.20	0.20	0.20
RHOB	Bulk density of the solid (grams/cubic centimeter)	1.6	1.6	1.6
THALF	Half-life of the solute	-	-	-
DEC1	Anaerobic decay coefficient (day^{-1})	0.004	0.004	0.004
DEC2	Reaeration coefficient (day^{-1})	0.00002	0.00002	0.00002
F	Stoichiometric Ratio of Hydrocarbons to Oxygen	3.1	3.1	3.1

[a/] Ns = Number of nodes that represent fluid sources (wells or constant head cells)
[b/] ADIP = Alternating-direction implicit procedure (subroutine for solving ground water flow equation)

Hydraulic conductivity is an important aquifer characteristic that determines the ability of the water-bearing strata to transmit ground water. Transmissivity is the product of the hydraulic conductivity and the thickness of the aquifer. An accurate estimate of hydraulic conductivity is important to help quantify advective ground water flow velocities and to define the flushing potential of the aquifer and the quantity of electron-acceptor-charged ground water that is entering the site from upgradient locations. Based on the work of Rifai *et al.* (1988), the Bioplume II model is particularly sensitive to variations in hydraulic conductivity. Lower values of hydraulic conductivity result in a slower-moving plume that degrades more slowly because less oxygen, nitrate, iron, sulfate, and carbon dioxide are available for biodegradation. Higher values of hydraulic conductivity result in a faster-moving plume that degrades faster because more electron acceptors are available for biodegradation.

Saturated thickness data from previous reports, geologic logs, and water level measurements were used in conjunction with the average hydraulic conductivity as determined from slug tests to estimate an initial uniform transmissivity for the entire model domain. To better match heads in the model to observed values, the transmissivities were progressively varied in blocks and rows until the simulated water levels for cells corresponding to the selected well locations matched the observed water levels as closely as possible. Figure 5.2 shows the calibrated water table. Calibrated model hydraulic conductivities ranged between 2.3×10^{-4} feet per second (ft/sec) and 6.5×10^{-4} ft/sec (1.4×10^{-2} ft/min to 3.9×10^{-2} ft/min).

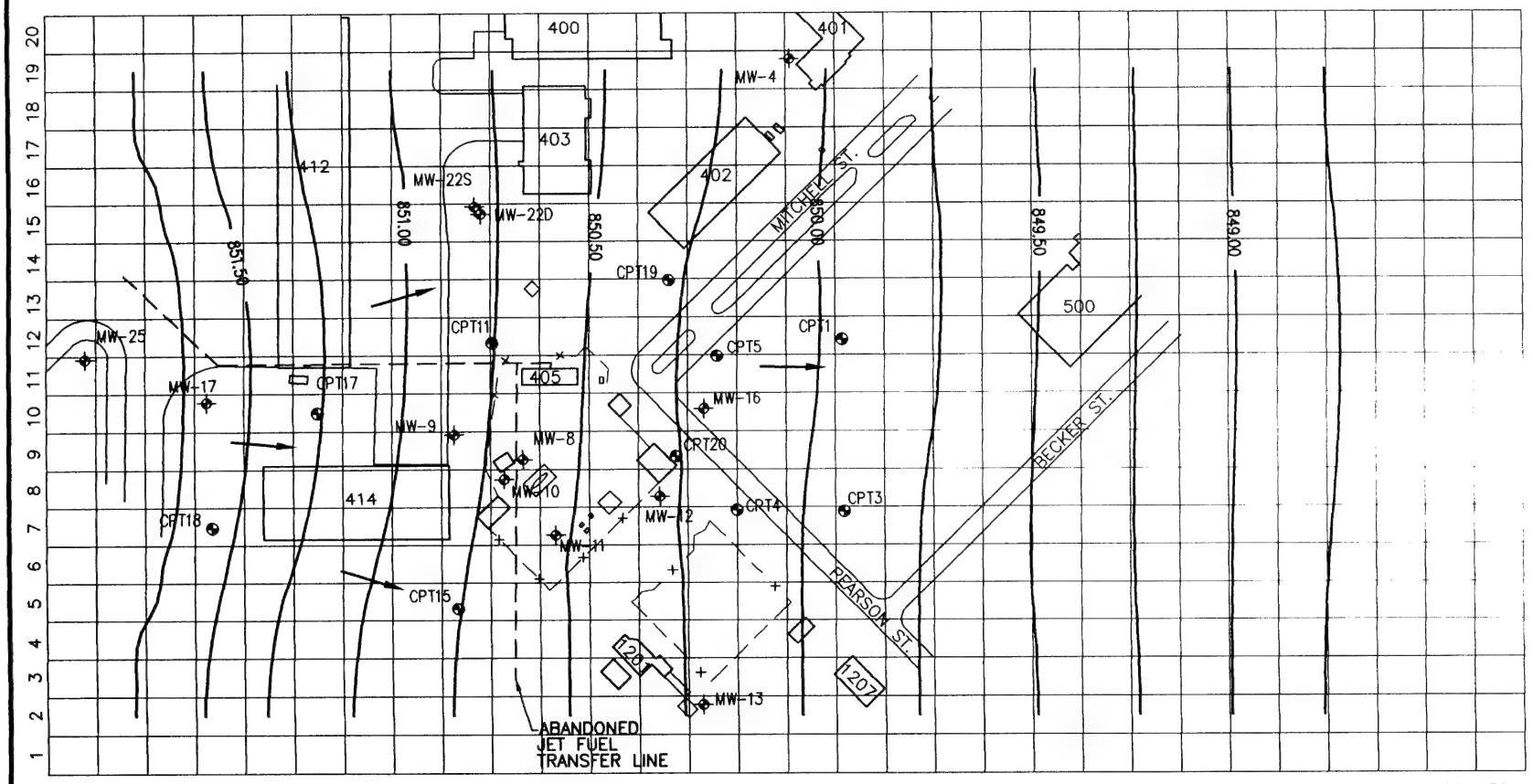
Water level elevation data from 15 monitoring well locations were used to compare measured and simulated heads for calibration. The 15 selected locations were MW-4, MW-9, MW-10, MW-11, MW-12, MW-17, MW-22S, CPT1, CPT4, CPT5, CPT15, CPT17, CPT18, CPT19, and CPT20.

The root mean squared (RMS) error is commonly used to express the average difference between simulated and measured heads. RMS error is the average of the squared differences between measured and simulated heads, and can be expressed as:

$$\mathrm{RMS} = \left[\frac{1}{n} \sum_{i=1}^{n} \left(h_m - h_s \right)_i^2 \right]^{0.5}$$

Where: n = the number of points where heads are being compared

h_m = measured head value



0 150 300
FEET

LEGEND

- MW-4 — MONITORING WELL LOCATION
- CPT1 — GROUND WATER MONITORING POINT
- —x— FENCE
- 402 BUILDING
- APPROXIMATE GROUND WATER FLOW DIRECTION
- —850.00— LINE OF EQUAL GROUND WATER ELEVATION (DASHED WHERE INFERRED)
- CONTOUR INTERVAL = 0.25 FEET

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FIGURE 5.2

CALIBRATED WATER TABLE MAP

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

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Denver, Colorado

h_s = simulated head value.

The RMS error between observed and calibrated values at the 15 comparison points was 0.059 foot, which corresponds to a calibration error of 1.8 percent (water levels dropped about 3.3 feet over the length of the model grid). RMS error calculations are summarized in Appendix C. A scatter plot of measured heads vs. simulated heads should is also useful for judging model calibration. Deviation of the plotted points from a straight line should be randomly distributed (Anderson and Woessner, 1992), as is the case for the scatter plot presented in Appendix C.

In solving the ground water flow equation, Bioplume II establishes the water table surface and calculates an overall hydraulic balance that accounts for the numerical difference between flux into and out of the system. The hydraulic mass balance for the calibrated model was excellent, with 99.99 percent of the water flux into and out of the system being numerically accounted for (i.e., a 0.01-percent error). According to Anderson and Woessner (1992), a mass balance error of around 1 percent is acceptable, while Konikow (1978) indicates an error of less than 0.1 percent is ideal.

5.4.2 BTEX Plume Calibration

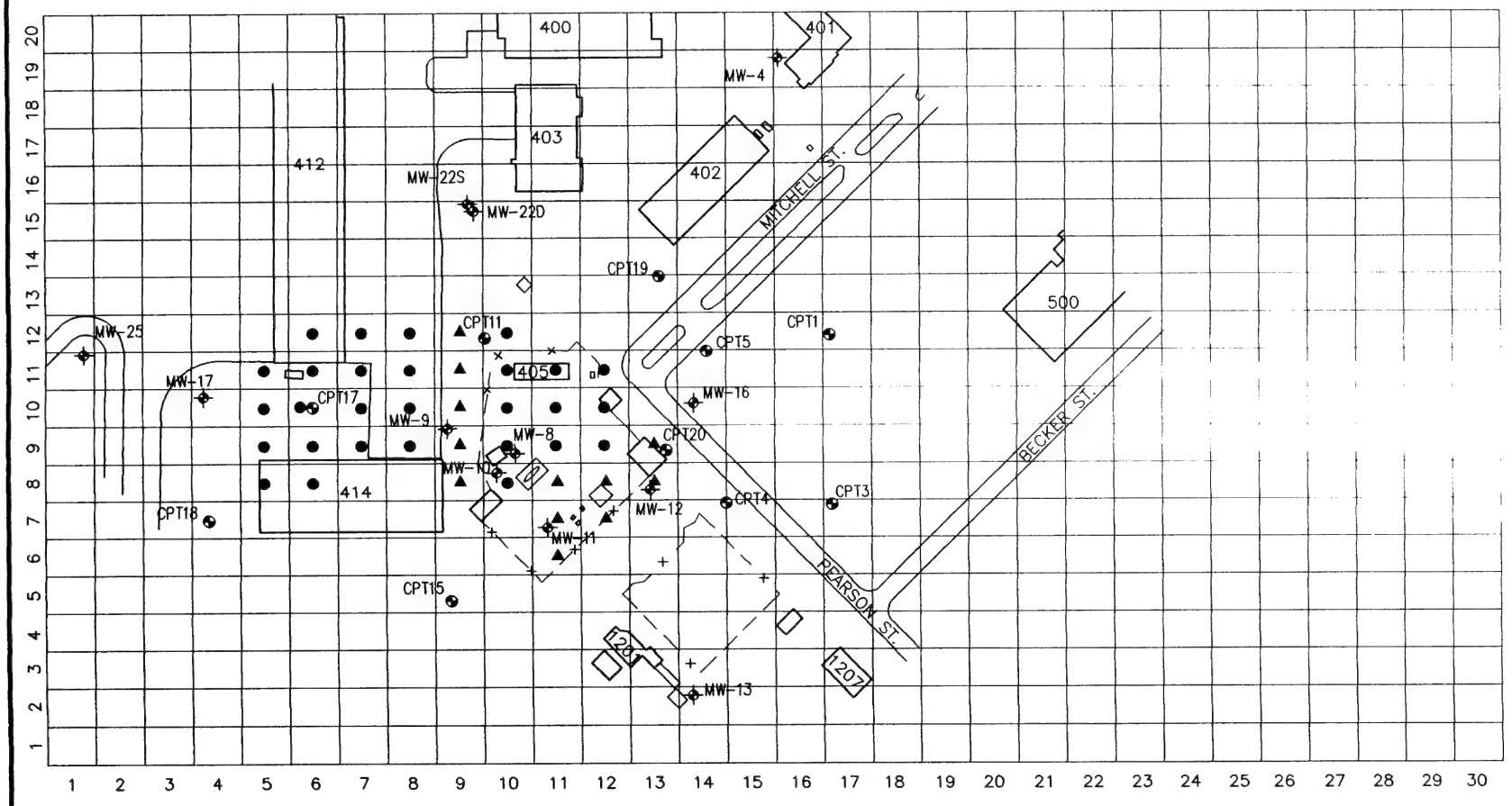
Model input parameters affecting the distribution and concentration of the simulated BTEX plume were modified so that model predictions matched dissolved total BTEX concentrations observed in September 1994. To do this, model runs were made using the calibrated steady-state hydraulic parameters. Calibration of the fate and transport portion of a Bioplume II model generally requires that the contaminant distribution be known for two different times. Contaminant data for the source areas from 1991 and 1992 were available (ASI, 1991; Dames & Moore, 1992a), but these data did not define the full downgradient extent of the plume. As a conservative assumption, it was assumed that the September 1994 plume extent could be used to estimate the extent of the 1991 plume for the initial model setup. Source removal through excavation south of Building 412 should not have affected BTEX concentrations near the plume margins, given that residual contamination probably remains below the water table in the excavation area and that the relatively low ground water velocity would minimize observable downgradient concentration changes. An initial plume configuration based on the source area BTEX concentrations measured in 1991, and on the plume extents observed in 1994, was estimated and gridded for model input.

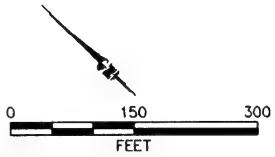
In addition, BTEX concentrations decreased at wells where samples were collected in both 1991 and 1994. Because local plume concentrations could be described at two different times (1991 and 1994), the plume calibration simulations were made with a time constraint of 3 years. In other words, computed BTEX plume concentrations and configurations were compared to September 1994 BTEX data after 3 years of simulation time incorporating injection, transport, and degradation of contaminants in ground water. It was assumed that during the calibration simulation, dissolved BTEX concentrations would decrease slightly in the source areas (as indicated by the available data), and that the resulting plume extent would approximate that observed in 1994.

Because residual LNAPL is present in the vicinity of the water table at the site, it was necessary to include simulated injection wells to model partitioning of BTEX compounds from the residual phase into the ground water. The location of the injection wells is shown on Figure 5.3. Locations of injection wells were based on the known location of the residual LNAPL and the extent of soil contamination indicated on Figure 4.1. It was also assumed that soil contamination was present under the southern end of Building 412 and the adjacent concrete aprons, and that residual contamination remained in saturated soil beneath the remedial excavation.

While the term "injection well" suggests contaminants are being introduced at a point, Bioplume II assumes that contamination introduced at a well instantly equilibrates throughout the entire cell in which the well is located. The injection rate for the cells was set at 5×10^{-5} cubic foot per second (ft^3/sec), a value low enough so that the flow calibration and water balance was not affected. Relatively high BTEX concentrations were injected in upgradient injection wells because of the low injection rate and the influx of oxygen introduced at the upgradient constant head cells. Replenishment of oxygen quickly degraded BTEX concentrations at the head of the plume, which in turn required larger injection concentrations of BTEX to produce observed BTEX contours. Because two source areas are present, wells with the highest BTEX injection concentrations were located in the vicinity of the excavation area south of Building 412 and in the vicinity of the POL Yard.

In addition to the injection of BTEX, DO was injected at locations where chemical data indicated that infiltrating precipitation replenishes electron acceptors. Locations of these injection wells are also indicated on Figure 5.3. After considering the assumptions outlined in Section 5.3.4, it was assumed that the initial DO concentrations in the shallow





LEGEND

- MW-4 ⊕ MONITORING WELL LOCATION
- CPT1 ⊕ GROUND WATER MONITORING POINT
- —x— FENCE
- 402 BUILDING
- ● LOCATION OF SIMULATED BTEX INJECTION WELL
- ▲ LOCATION OF SIMULATED OXYGEN INJECTION WELL

FIGURE 5.3

LOCATION OF SIMULATED INJECTION WELLS FOR MODEL CALIBRATION AND PREDICTION

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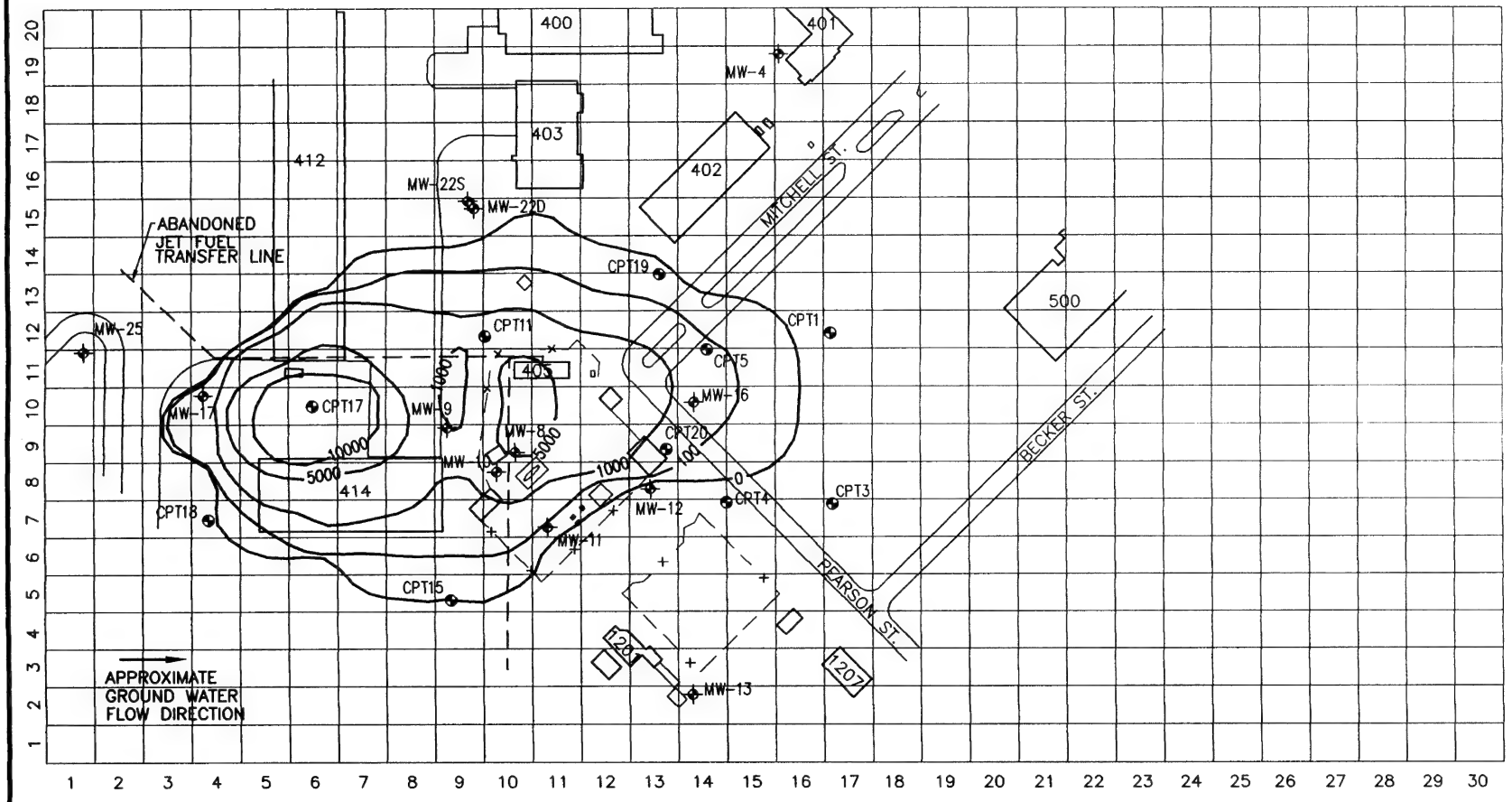
aquifer were similar to those observed in 1994, and that water with DO concentrations between 2 and 5 mg/L would be continually introduced at the northwestern boundary.

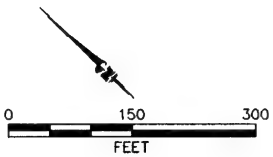
Total BTEX and DO injection concentrations were determined by varying the injection concentration for the various wells until the modeled total BTEX plume approximated the total BTEX plume observed in September 1994. Because residual hydrocarbons remain below the water table in the excavation area south of Building 412, and because contaminated soil probably remains beneath the building and the concrete pads, it was assumed for calibration purposes that BTEX injection concentrations in that source area would not immediately diminish. By varying the injection well concentrations, the coefficient of retardation, dispersivity, the anaerobic decay coefficient, and the reaeration coefficient, the BTEX plume was calibrated reasonably well to the existing plume in terms of plume extent and BTEX concentrations in the source areas. The calibrated plume configuration is shown on Figure 5.4.

The calibrated model plume is very similar, but not identical, to the observed BTEX plume (Figure 4.2). The total area of the simulated BTEX plume is comparable to the plume observed in 1994. The simulated and observed 10,000-µg/L isopleths are similar in shape, and the simulated BTEX concentrations in the two source areas are similar to those observed at CPT17 (south of Building 412) and MW-8 (in the POL yard). In some locations, the computed plume has concentrations higher than those observed in 1994. For example, the area of the computed 1,000-µg/L isopleth is noticeably larger than that indicated by the observed concentrations. In addition, the areas of low BTEX concentrations in the vicinities of MW-9, MW-11, and MW-12 were reproduced.

The maximum simulated total BTEX concentration was 21,289 µg/L for the cell 10,6 (in the vicinity of CPT17). The computed plume does not have concentrations as high as the concentration observed at CPT17 (28,000 µg/L). However, the measurement at CPT17 was made at a point, while the model is indicating a concentration that is averaged for the entire model cell representing that area.

The downgradient margin of the calibrated plume did not extend as far as indicated by Figure 4.2. This is a result of the way in which Bioplume II simulated anaerobic biodegradation. The anaerobic decay constant is applied to all simulated BTEX concentrations, whereas aerobic degradation is actually the dominant process at the margins of the plume and possibly in the areas where precipitation recharge is concentrated. This results in a slightly shorter simulated plume (approximately 75 feet





LEGEND

- MW-4 ⊕ MONITORING WELL LOCATION
- CPT1 ◉ GROUND WATER MONITORING POINT
- —×— FENCE
- 402 BUILDING
- —5000— LINE OF EQUAL SIMULATED BTEX CONCENTRATION (µg/L)
  CONTOUR INTERVAL = VARIABLE

FIGURE 5.4

CALIBRATED BTEX PLUME

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shorter). For these same reasons, the simulated plume is also slightly narrower than the observed plume. However, the computed distribution represents a greater total mass of BTEX because many concentrations are higher than those observed, and because the model assumes that contamination extends throughout the total depth of the aquifer. In reality, the plume is only present in a portion of the total aquifer thickness, and concentrations appear to diminish with depth. Because of this, and because the calibrated model BTEX concentrations are similar to the observed concentrations, the predictions made by this model should be conservative.

5.4.2.1 Discussion of Parameters Varied During Plume Calibration

As noted previously, the transport parameters varied during plume calibration were dispersivity, the coefficients of retardation and reaeration, and the anaerobic decay coefficient. These parameters were varied with intent of limiting plume migration to the observed extents, because original estimates for the parameters resulted in a calculated BTEX plume distribution that did not reproduce the observed plume. While these parameters were varied with this common intent, each had a slightly different impact on the size and shape of the simulated plume.

5.4.2.1.1 Dispersivity

Much controversy surrounds the concepts of dispersion and dispersivity. Longitudinal dispersivity values for sediments similar to those found at the site range from 0.1 to 200 feet (Walton, 1988). To be conservative, longitudinal dispersivity was originally estimated as 10 feet Transverse dispersivity values generally are estimated as one-tenth (0.1) of the longitudinal dispersivity values (Domenico and Schwartz, 1990). However, because the plume was relatively wide relative to the known source areas, the initial model input assumed a ratio of 0.25.

During plume calibration, longitudinal dispersivity was raised to 25 feet from the original estimate of 10 feet. This was done in an attempt to extend the computed plume margin downgradient far enough to approximate the observed plume margin and also to help increase the lateral extent of the plume to better match the observed extents.

5.4.2.1.2 Anaerobic Decay Coefficient

As discussed in Section 5.3.5, the anaerobic decay coefficient was originally estimated to be 0.004 day^{-1}. This value was varied during plume calibration, but the calibrated model used the original estimate. This prevented the plume from migrating too far in the calibration run, and at the same time prevented contaminant concentrations in the center portion of the plume from being excessively high.

5.4.2.1.3 Coefficient of Retardation

Retardation of the BTEX compounds relative to the advective velocity of the ground water occurs when BTEX molecules are sorbed to the aquifer matrix. Based on measured TOC concentrations in the saturated zone at four locations, and assuming a bulk density of 1.6 grams/cubic centimeter (Freeze and Cherry, 1979), and published values of the soil sorption coefficient (K_{oc}) for the BTEX compounds (as listed in Wiedemeier *et al.*, 1994), the coefficients of retardation for the BTEX compounds were calculated. The results of these calculations are summarized in Table 5.2. To be conservative, the minimum range of retardation coefficients calculated for the BTEX compounds (1.42 to 3.57, for benzene) was used as a constraint for model input. The coefficient of retardation originally used as model input was 1.8. The lower the assumed coefficient of retardation, the farther the BTEX plume will migrate downgradient.

During plume calibration, the coefficient of retardation was gradually raised from the initial value of 1.8 to a value of 2.06. This variable was altered in response to model predictions of high BTEX concentrations in the vicinity of MW-9 and in the area downgradient of the POL yard. In addition, increasing the value of this parameter was also necessary to limit the contaminants' rate of travel.

5.4.2.1.4 Reaeration Coefficient

The reaeration coefficient is a first-order rate constant used by Bioplume II to simulate the replenishment of oxygen into the ground water by soil gas diffusion and rainwater infiltration. Because most of the plume area is covered with pavement or buildings, a relatively low reaeration coefficient of 0.00002 day^{-1} was originally estimated. This is much lower than has been used in other documented Bioplume modeling efforts (for example, Rifai *et al.*, 1988 used a value of 0.003 day^{-1}). Use of a reaeration coefficient is justified at this site because of the shallow water table and the DO concentrations

TABLE 5.2

CALCULATION OF RETARDATION COEFFICIENTS
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Compound	K_{oc} (L/kg [a/])	Maximum Fraction Organic Carbon [b/]	Minimum Fraction Organic Carbon [b/]	Average Fraction Organic Carbon [b/]	Distribution Coefficient K_d (L/kg) Maximum [c1/]	Minimum [c2/]	Average [c3/]	Bulk Density (kg/L) [d/]	Effective Porosity	Coefficient of Retardation Maximum	Minimum	Average
Benzene	79	0.0061	0.001	0.0024	0.482	0.079	0.190	1.60	0.30	3.57	1.42	2.01
Toluene	190	0.0061	0.001	0.0024	1.159	0.190	0.456	1.60	0.30	7.18	2.01	3.43
Ethylbenzene	468	0.0061	0.001	0.0024	2.855	0.468	1.123	1.60	0.30	16.23	3.50	6.99
m-xylene	405	0.0061	0.001	0.0024	2.471	0.405	0.972	1.60	0.30	14.18	3.16	6.18
o-xylene	422	0.0061	0.001	0.0024	2.574	0.422	1.013	1.60	0.30	14.73	3.25	6.40
p-xylene	357	0.0061	0.001	0.0024	2.178	0.357	0.857	1.60	0.30	12.61	2.90	5.57

NOTES:

[a/] From technical protocol document A7(Wiedemeier *et al.*, 1994)

[b/] From site data

[c1/] K_d = Maximum Fraction Organic Carbon x K_{oc}

[c2/] K_d = Minimum Fraction Organic Carbon x K_{oc}

[c3/] K_d = Average Fraction Organic Carbon x K_{oc}

[d/] Literature values

observed outside of the plume. The reaeration coefficient had little effect on plume migration and was left at its originally estimated value of 0.00002 day^{-1}.

5.5 SENSITIVITY ANALYSIS

The purpose of the sensitivity analysis is to determine the effect of varying model input parameters on model output. Based on the work of Rifai *et al.* (1988), the Bioplume II model is typically most sensitive to changes in the coefficient of reaeration, the coefficient of anaerobic decay, and the hydraulic conductivity of the media, and is less sensitive to changes in the retardation factor, porosity, and dispersivity. The sensitivity analysis for this model was conducted by varying transmissivity, the coefficient of retardation, the coefficient of anaerobic decay, dispersivity, and the coefficient of reaeration.

To perform the sensitivity analyses, individual runs of the plume calibration model were made with the same input as the calibrated model, except that one of the aforementioned parameters was varied. The models were run for a 3-year period, just as the original was, so that the independent effect of each variable could be assessed. As a result, 10 sensitivity runs of the calibrated model were made, with the following variations:

1) Transmissivity uniformly increased by a factor of 5;

2) Transmissivity uniformly decreased by a factor of 5;

3) Coefficient of retardation increased to 3.0;

4) Coefficient of retardation decreased to 1.0;

5) Coefficient of anaerobic decay increased by a factor of 5;

6) Coefficient of anaerobic decay decreased by a factor of 5;

7) Longitudinal dispersivity increased by a factor of 2;

8) Longitudinal dispersivity decreased by a factor of 2;

9) Reaeration coefficient increased by a factor of 5; and

10) Reaeration coefficient decreased by a factor of 5;

The results of the sensitivity analyses are shown graphically in Figures 5.5, 5.6, 5.7, 5.8, and 5.9. These figures display the modeled BTEX concentrations versus distance

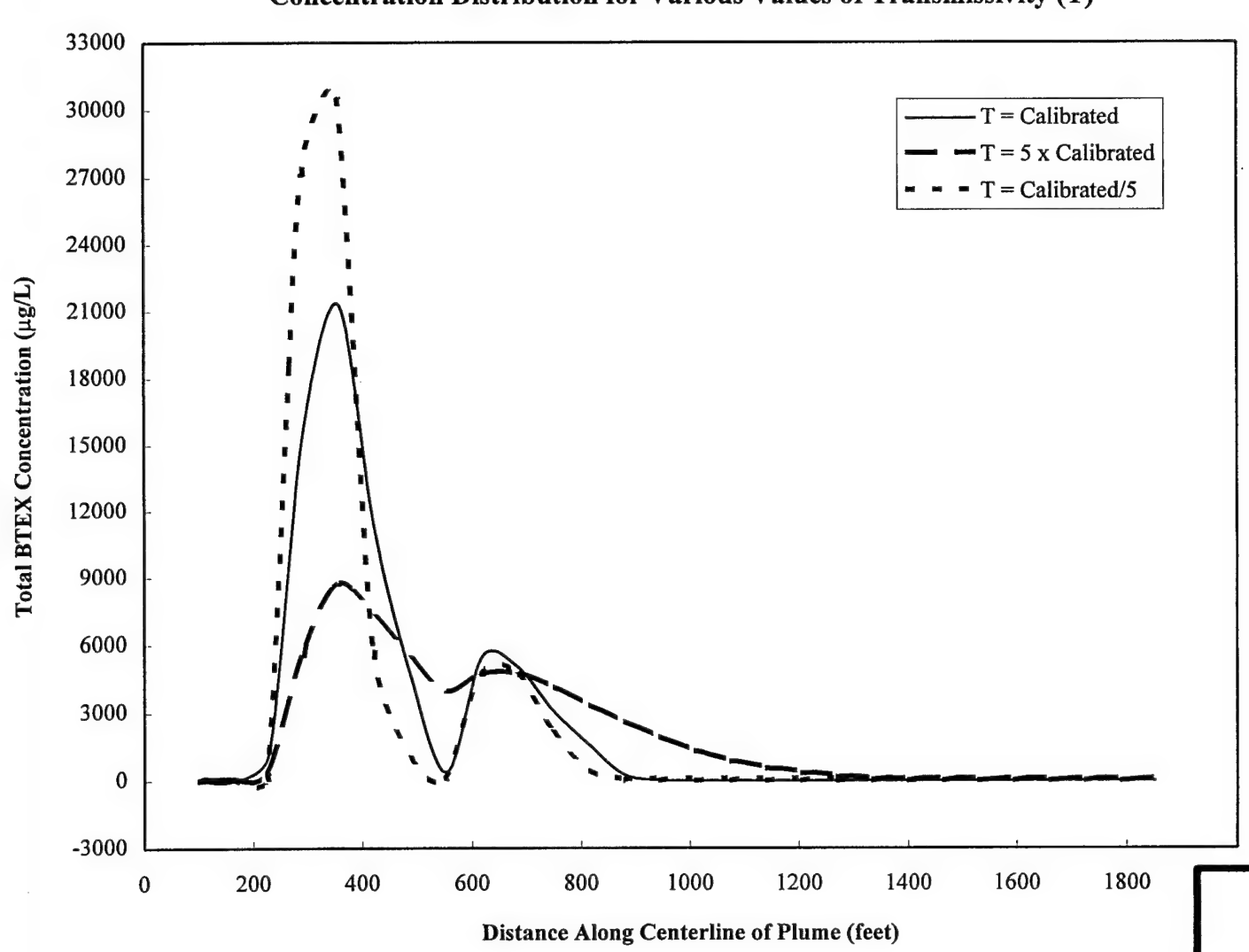

FIGURE 5.5

MODEL SENSITIVITY TO VARIATIONS IN TRANSMISSIVITY

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Concentration Distribution for Various Values of the Coefficient of Retardation (R)

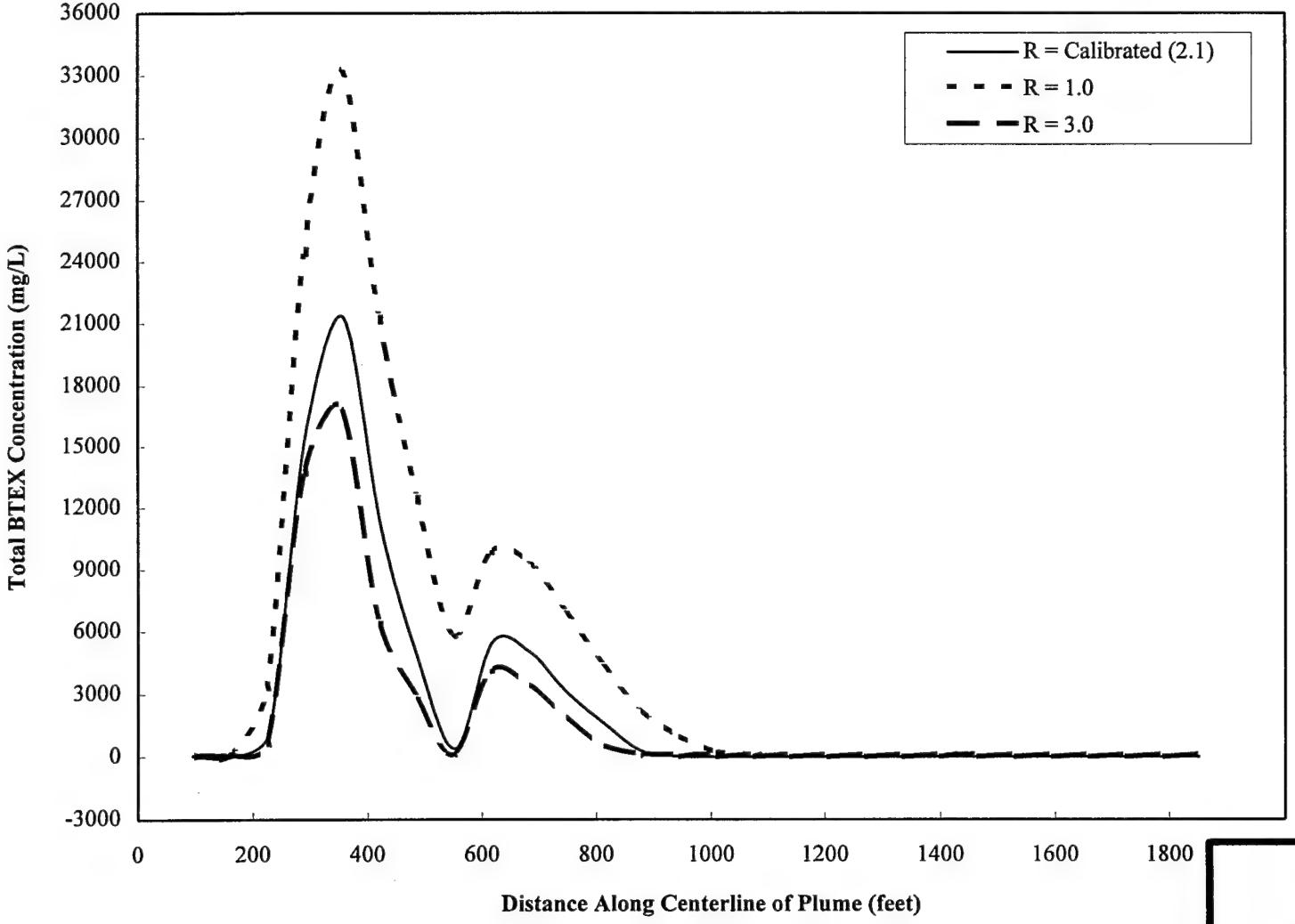

FIGURE 5.6

MODEL SENSITIVITY TO VARIATIONS IN THE COEFFICIENT OF RETARDATION

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Wisconsin Air National Guard at Truax Field
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Concentration Distribution for Various Values of the Coefficient of Anaerobic Decay (DEC1)

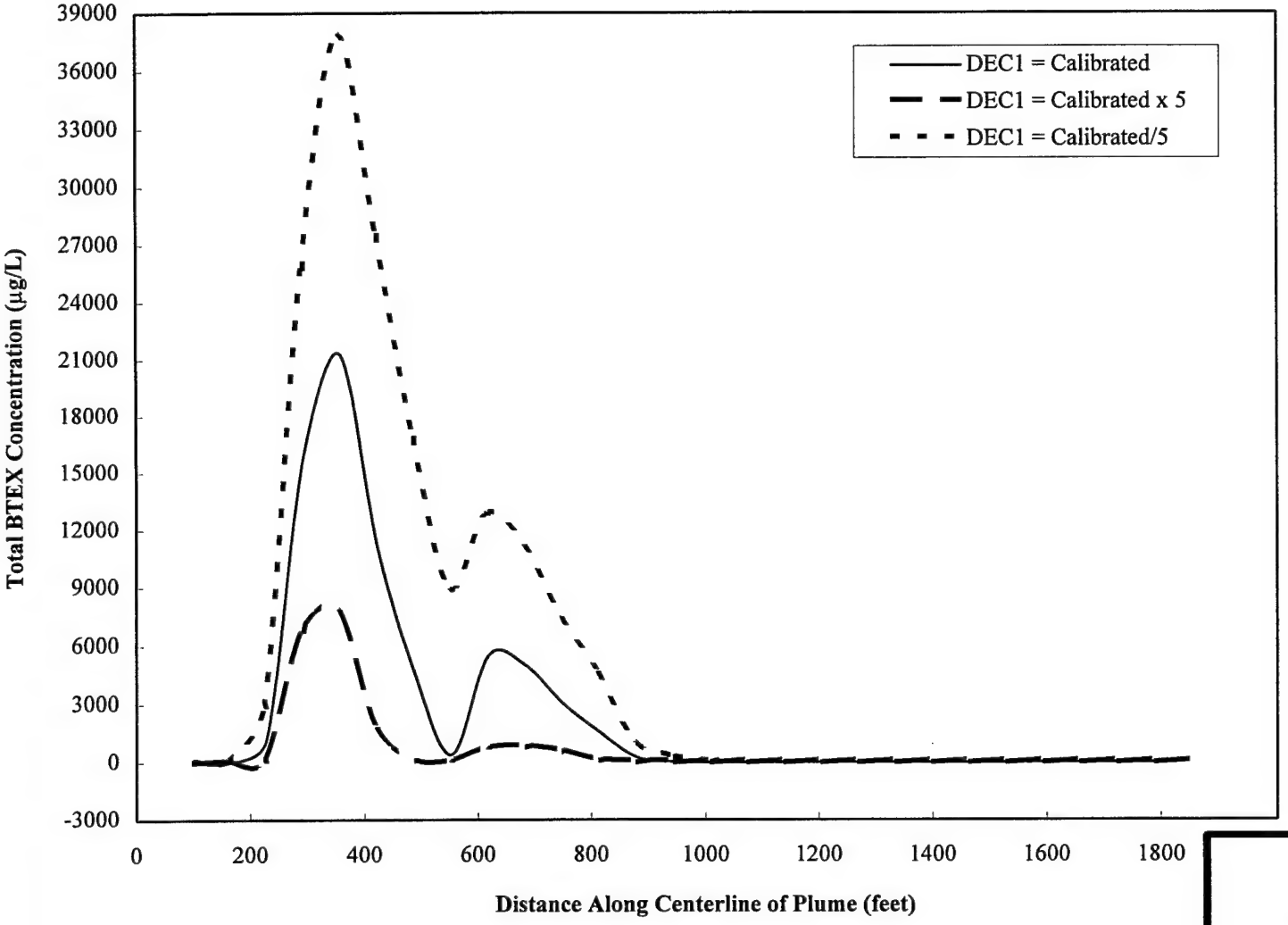

FIGURE 5.7

MODEL SENSITIVITY TO VARIATIONS IN THE ANAEROBIC DECAY COEFFICIENT

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Wisconsin Air National Guard at Truax Field
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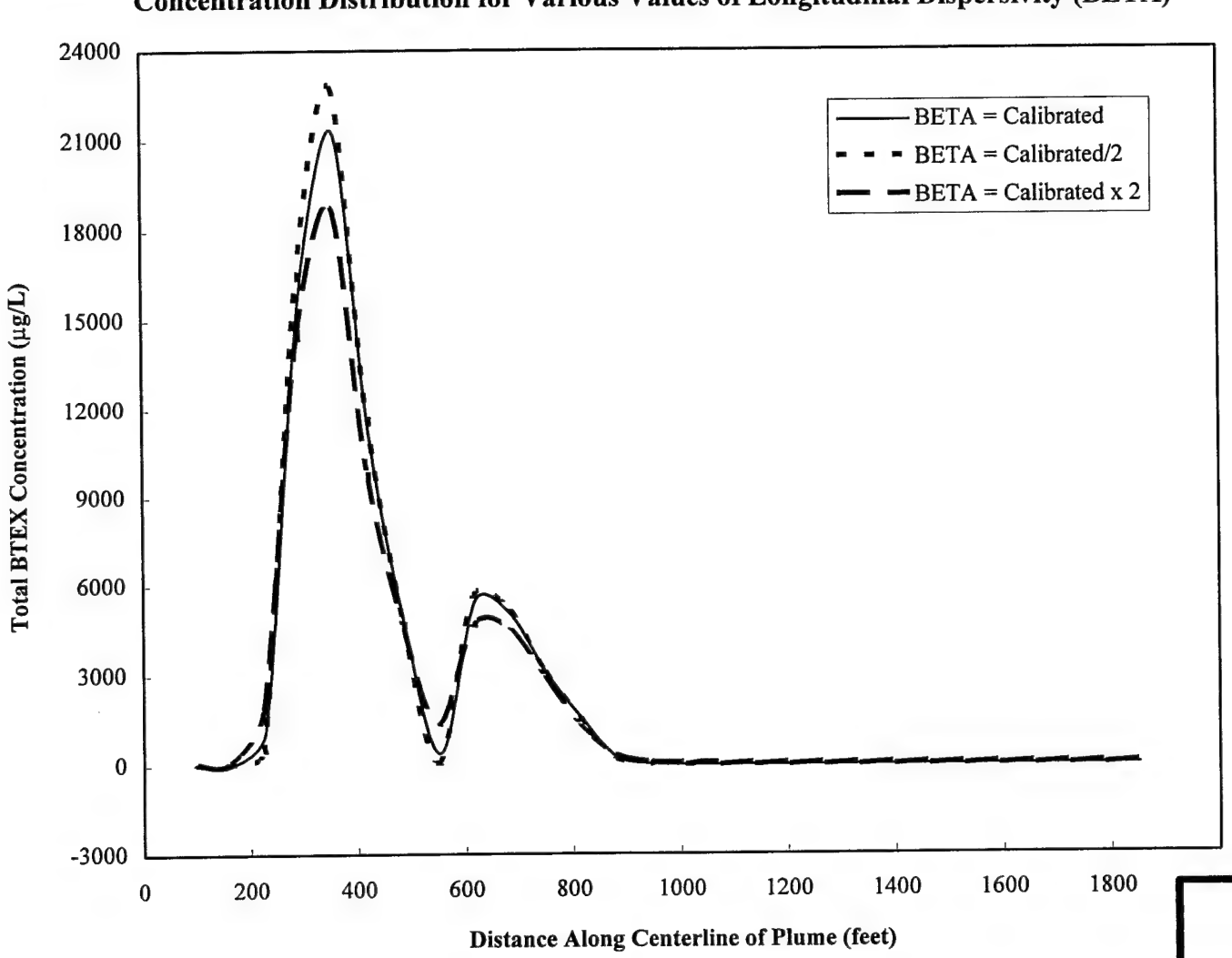

FIGURE 5.8

MODEL SENSITIVITY TO VARIATIONS IN DISPERSIVITY

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

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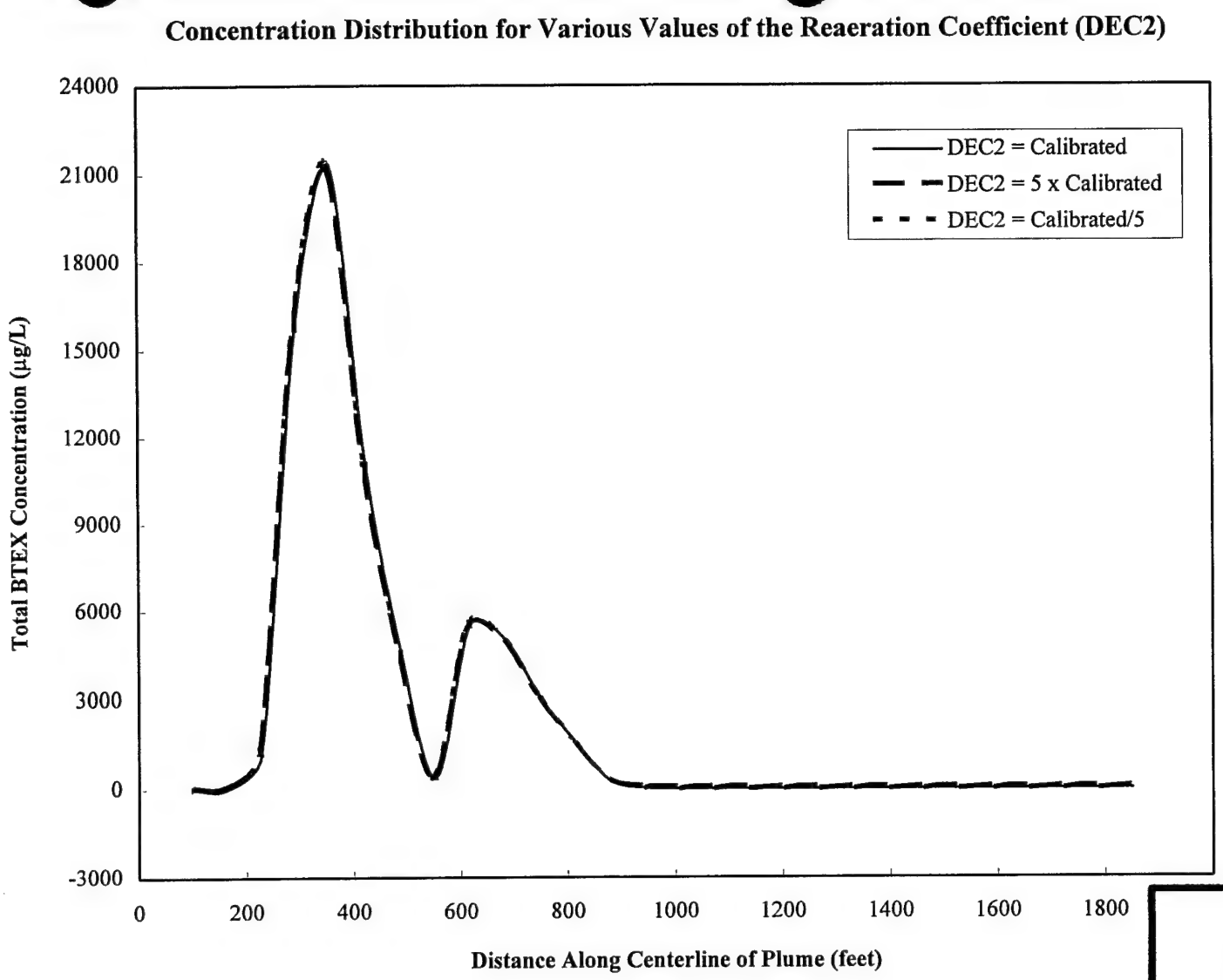

FIGURE 5.9

MODEL SENSITIVITY TO VARIATIONS IN THE REAERATION COEFFICIENT

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Madison, Wisconsin

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along the centerline of the plume (in the tenth model column). This manner of displaying data is useful because BTEX concentrations are highest in the tenth model column, the plume is relatively symmetrical, and the plume migrates in a direction parallel to the model grid. Furthermore, the figures allow easy visualization of the changes in BTEX concentration caused by varying model input parameters.

The effects of varying transmissivity are shown by Figure 5.5. Uniformly increasing the transmissivity by a factor of five increased the biodegradation rate and spreading of the plume such that the maximum observed concentrations in the source cell area were only about 9,000 µg/L, compared to the calibrated maximum of 21,289 µg/L. In addition, the leading edge of the BTEX plume was approximately 400 feet farther downgradient than in the calibrated model. Increased biodegradation results from a greater flux of water through the model area bringing a greater mass of DO contact with the plume. Because more DO is available, aerobic biodegradation occurs more rapidly. Also, the faster ground water velocity produced by the higher transmissivity initially results in greater plume travel rates and distances, spreading out and further exposing the BTEX plume to oxygenated water. In contrast, decreasing the transmissivity by a factor of five slowed overall plume migration, which shortened the plume and in turn caused an increase in maximum BTEX levels. Increased BTEX concentrations in the plume area are caused by reductions in the plume travel rate and the amount of oxygen being brought into contact with the contaminants from upgradient locations.

The effects of varying the coefficient of retardation (R) are shown on Figure 5.6. Increasing R to 3.00 results in the maximum BTEX concentration decreasing by approximately 5,000 µg/L, and the plume is approximately 100 feet shorter than in the calibrated model. On the other hand, decreasing R to 1.00 (no retardation) produces a plume that extends about 150 feet further downgradient than the original model plume and that has a much higher maximum concentrations in the source areas. These results suggest that the R used for the calibrated simulation is acceptable, because the model is less sensitive to higher values of R, while a value of R that is too low will result in a simulated plume that travels beyond the limits of the observed plume and that has unacceptably high concentrations in the source areas.

Figure 5.7 shows the effects of varying the anaerobic decay coefficient. Increasing this parameter by a factor of five results in rapid degradation of dissolved BTEX. This significant reduction in contaminant mass is the result of the large increase in the decay

rate caused by increasing the coefficient, because the anaerobic decay coefficient is exponentiated in the equation expressing the decay rate (see Section 5.3.5). Conversely, decreasing the anaerobic decay coefficient by a factor of five greatly decreases the rate of degradation, resulting in a large increase of the computed maximum BTEX concentrations to approximately 38,500 µg/L and a slight increase in plume length. Thus, the model is also sensitive to this coefficient, suggesting that a reasonable value was used in the calibrated model.

The effects of varying dispersivity are illustrated by Figure 5.8. Both longitudinal and transverse dispersivity were varied for this analysis, as the ratio of the two values was kept constant at 0.25. Increasing the dispersivity by a factor of two resulted in slightly lower maximum BTEX concentrations although the plume was spread out over a similar area. Decreasing dispersivity by a factor of two produced a plume with an extent similar to the calibrated plume, but with slightly higher concentrations. The model appears to be relatively insensitive to dispersivity within the range of reasonable values evaluated for this analysis.

The effects of varying the reaeration coefficient are illustrated by Figure 5.9. Increasing or decreasing this parameter by a factor of five results in virtually no change in the BTEX plume configuration. As indicated by Rifai *et al.* (1988), Bioplume II simulations typically are quite sensitive to this parameter. However, this particular model is relatively insensitive to this parameter because a very low value was used for model calibration.

The results of the sensitivity analysis suggest that the calibrated model used for this report is reasonable. The calibrated model is most sensitive to transmissivity and the anaerobic decay coefficient, although the coefficient of retardation is also an important parameter. Increasing the anaerobic decay coefficient or the transmissivity greatly diminishes the predicted BTEX concentrations. Lowering the values of the anaerobic decay coefficient and the coefficient of retardation lengthens the plume beyond reasonable distances based on recent observations at the site. While the model appears relatively insensitive to dispersivity, adjustment of that parameter contributed toward producing an appropriate plume configuration. This particular simulation is insensitive to the range of reaeration coefficients examined in this sensitivity analysis.

5.6 MODEL RESULTS

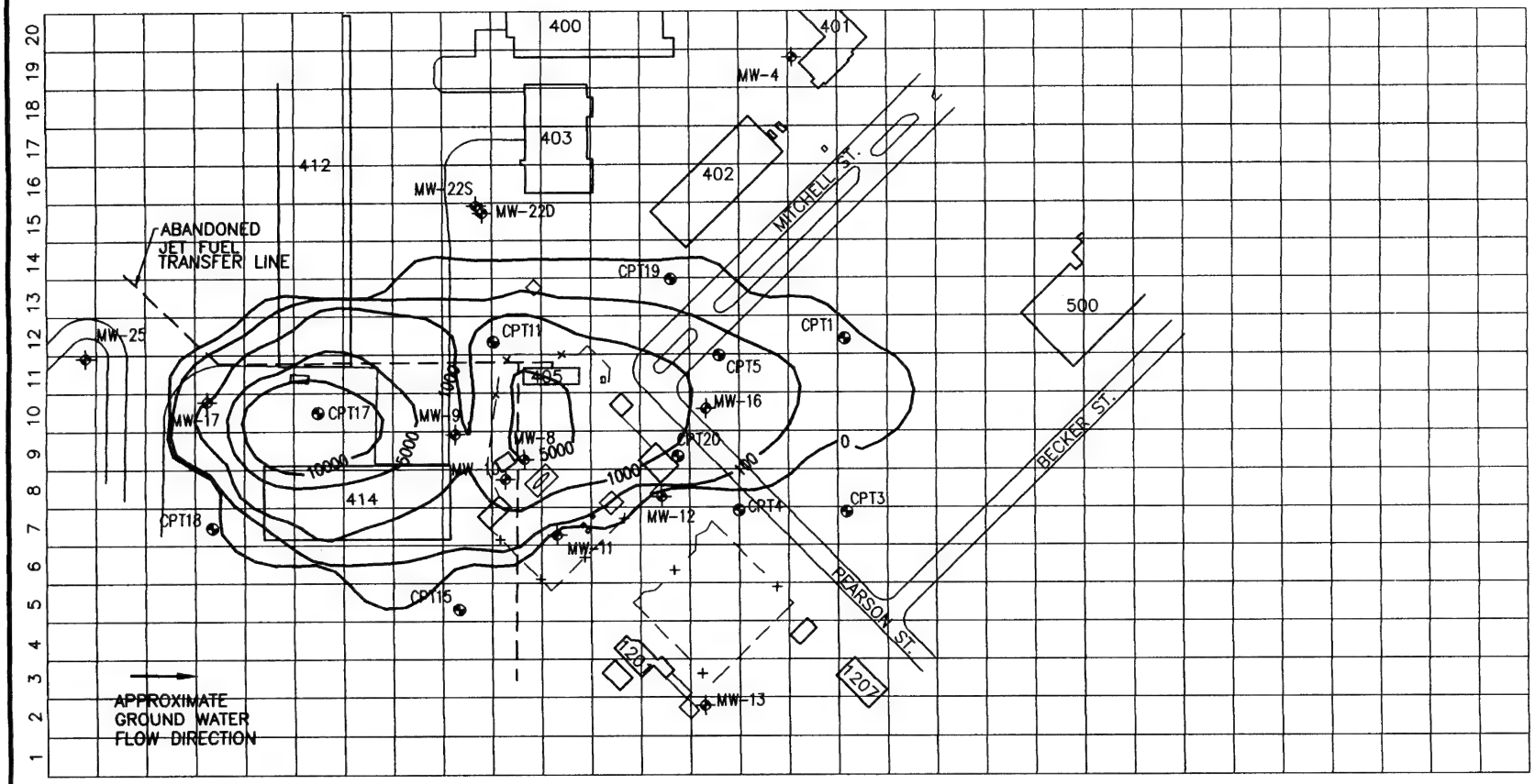
To predict fate and transport of dissolved BTEX compounds at the Truax Field site, two Bioplume II simulations (MAD_B and MAD_C) were run under steady-state conditions. The first simulation was based on the assumption that the conditions that produced the calibrated model remain constant, including the rates at which BTEX and DO are introduced to the aquifer through injection wells. The second simulation incorporated a reduction in BTEX loading rates based on the assumption that the source areas would be remediated over a period of about 4 years. Complete input and output files are presented in Appendix D. Model results are described in the following sections.

5.6.1 Continuation of Calibrated Conditions (Model MAD_B)

Model MAD_B was used to simulate the migration and biodegradation of the BTEX plume assuming that the conditions that produced the calibrated model continue, including continuing sources of dissolved BTEX compounds. The calibrated simulation was run to predict conditions up to 30 years beyond the original calibrated model end time, or 30 years beyond 1994. This model does not account for partial source removal (accomplished by excavation and treatment of soils using low-temperature thermal desorption) in the area south of Building 412. As a result, the results of this simulation should provide a conservative prediction of plume migration.

Figure 5.10 shows the plume after 5 years of simulation time. Modeled BTEX concentrations rise slightly, to a maximum of 21,500 μg/L, and the plume (as defined by the 0 μg/L isopleth) is approximately 65 feet longer than the plume observed in September 1994. After 10 years of simulation time (Figure 5.11), the maximum simulated BTEX concentration is 22,205 μg/L, and the leading edge of the plume reaches approximately 125 feet farther than observed in 1994. Beyond 10 years of simulation time the plume stabilizes, with a configuration similar to that predicted for 10 years beyond 1994. Figure 5.12 shows the stabilized BTEX plume after 30 years of prediction time. After the plume stabilizes, the maximum concentration (in the source area) varies between 21,300 and 22,300 μg/L.

These results suggest that the observed BTEX plume is approaching a stable configuration, and should stabilize in about 10 years. Stabilization of a plume reflects a configuration in which the downgradient portion of the plume is attenuated by dispersion,



LEGEND

MW-4 ⊕ MONITORING WELL LOCATION

CPT1 ⊕ GROUND WATER MONITORING POINT

—×— FENCE

402 BUILDING

—5000— LINE OF EQUAL SIMULATED BTEX CONCENTRATION (µg/L)
CONTOUR INTERVAL = VARIABLE

0 150 300
FEET

FIGURE 5.10

PREDICTED BTEX PLUME AFTER 5 YEARS MODEL MAD_B CONTINUING SOURCE

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Wisconsin Air National Guard at Truax Field
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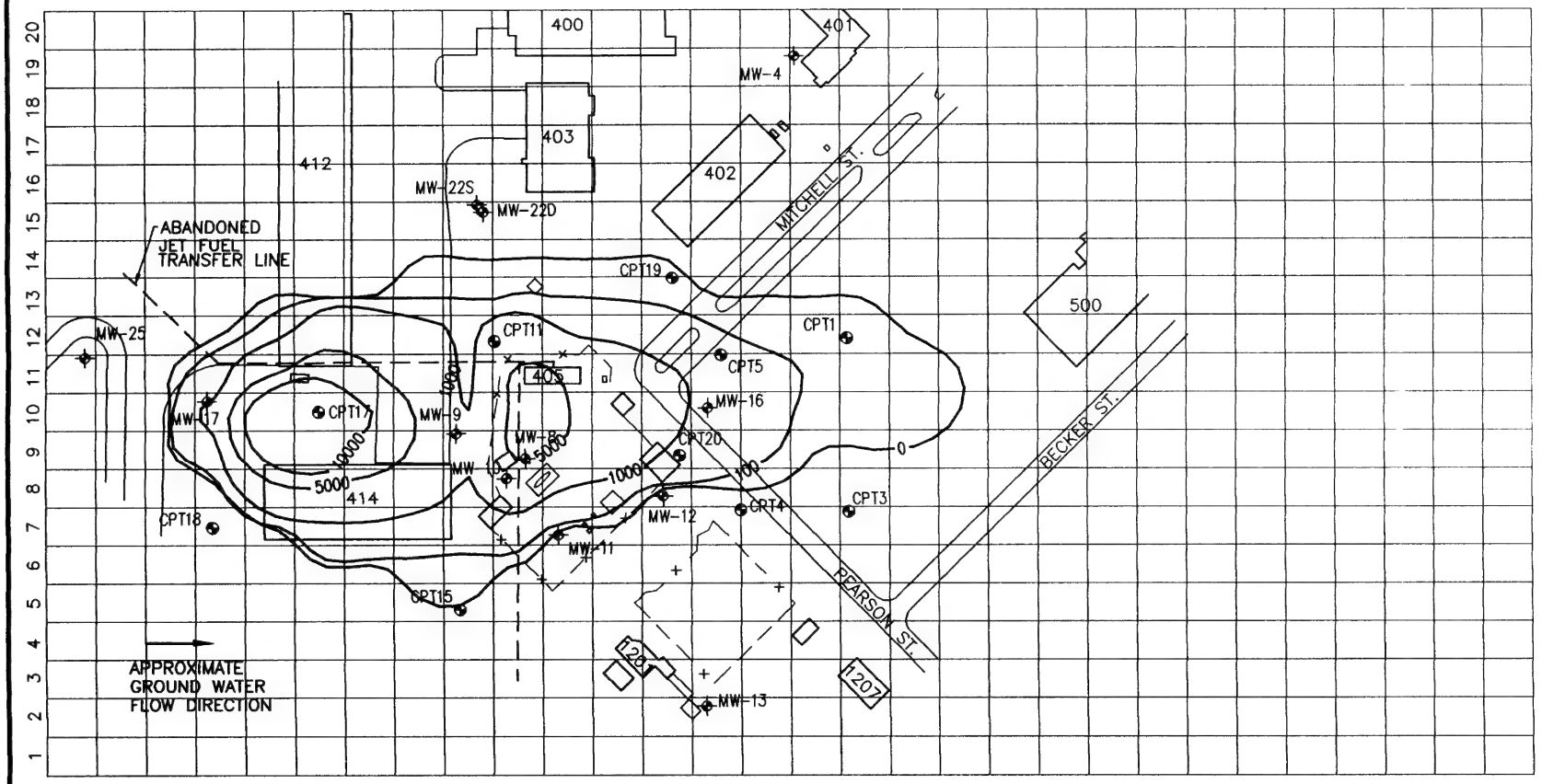

0 150 300
FEET

LEGEND

MW-4 ⊕ MONITORING WELL LOCATION

CPT1 ⊕ GROUND WATER MONITORING POINT

—x— FENCE

402 BUILDING

—5000— LINE OF EQUAL SIMULATED BTEX CONCENTRATION (µg/L)
CONTOUR INTERVAL = VARIABLE

M:\45009\DRAWINGS\95DN0053 01/17/95 ● 1315

FIGURE 5.11

PREDICTED BTEX PLUME AFTER 10 YEARS MODEL MAD_B CONTINUING SOURCE

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Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

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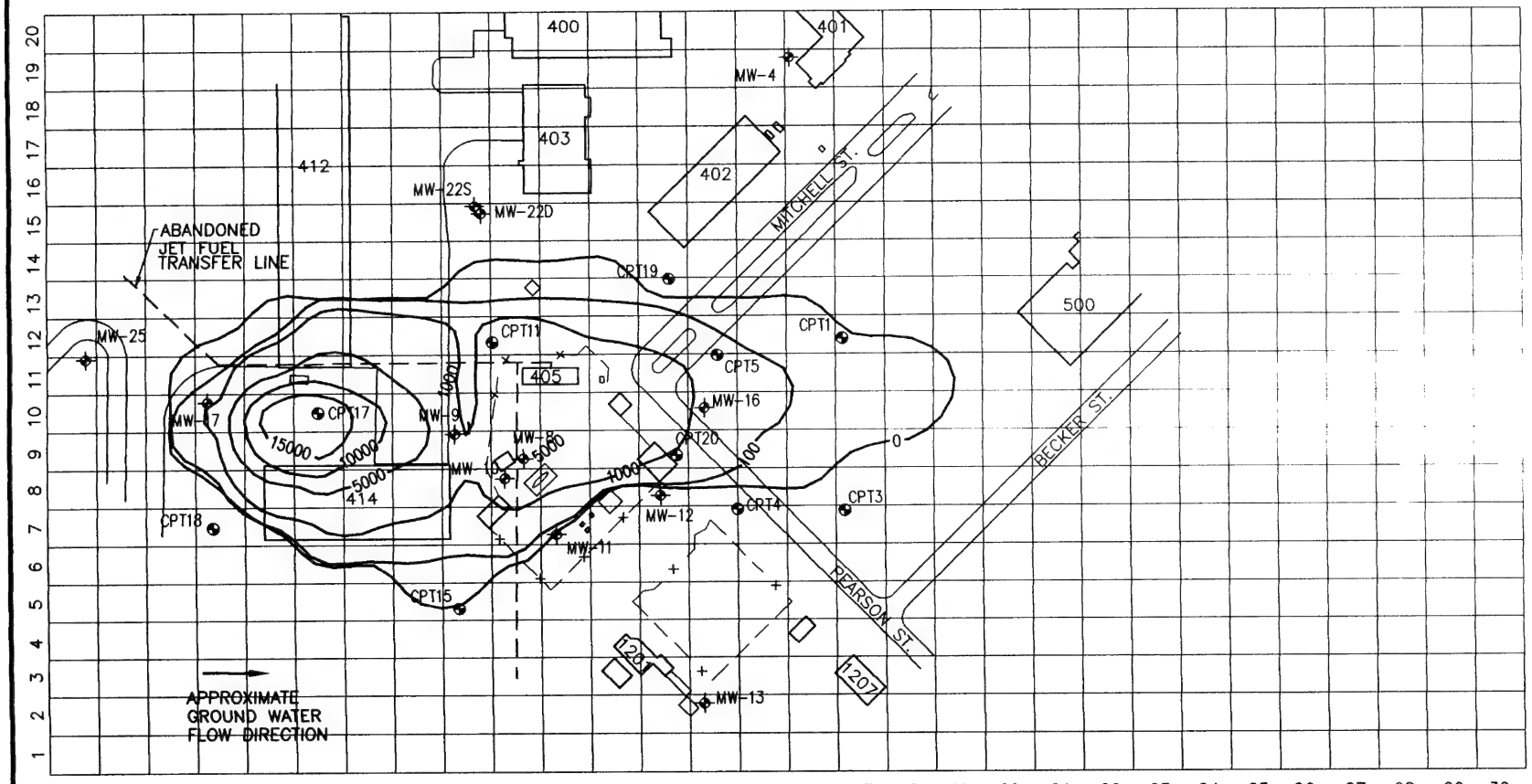

LEGEND

MW-4 ⊕ MONITORING WELL LOCATION

CPT1 ⊕ GROUND WATER MONITORING POINT

—×— FENCE

402 BUILDING

—5000— LINE OF EQUAL SIMULATED BTEX CONCENTRATION (μg/L)

CONTOUR INTERVAL = VARIABLE

0 150 300

FEET

FIGURE 5.12

PREDICTED BTEX PLUME AFTER 30 YEARS MODEL MAD_B CONTINUING SOURCE

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Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

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sorption, and biodegradation, but BTEX is replenished from the upgradient source at a rate sufficient to keep the plume front in a relatively stationary position. In actuality, as the residual hydrocarbons in the source area weather and degrade, BTEX loading rates would decrease and the plume would eventually recede after reaching its maximum extent. However, that retreat would be relatively slow, because hydrocarbons that were sorbed onto aquifer solids will eventually desorb as dissolved hydrocarbon concentrations decrease.

As a result of desorption, and as a result of the inability the model to accurately reproduce the full downgradient extent of plume front (as discussed in Section 5.4.2), it is likely that the plume front may extend slightly farther than predicted by this simulation. The plume is also likely to be wider than indicated by this simulation, as discussed in Section 5.4.2. It is not possible to quantify how much longer and wider the actual BTEX plume might be; however, it should be considered that the source loading is likely to diminish, and that the stable simulated plume is only about 125 feet longer than the observed plume. In addition, several conservative assumptions were made during the modeling process. Therefore, the plume migration indicated by model MAD_B is relatively conservative. It is unlikely that the actual downgradient plume migration would be more than twice that indicated (i.e., more than 250 feet beyond the front observed in September 1994).

5.6.2 Source Reduction (Model MAD_C)

Although some of the source area was excavated in the vicinity of Building 412 in fall 1993, it appears that residual hydrocarbons remain below the water table and continue to act as a source of dissolved BTEX, along with contaminated soil that likely remains beneath Building 412 and the concrete pad immediately southeast of the former excavation. In addition, no source reduction has been attempted in the vicinity of the POL Yard. To illustrate the impact of source reduction activities upon dissolved BTEX migration, model MAD_C incorporated decreasing BTEX loading rates, assuming that bioventing or a similar *in situ* method would be used to remediate the source areas.

Bioventing is an *in situ* process where low-flow air injection or extraction is used to enhance the biodegradation of organic contaminants in subsurface soils by supplying oxygen to indigenous microbes. A bioventing system may begin operation as an extraction system due to the high levels of petroleum hydrocarbons. After soil gas

concentrations are reduced, the system would be switched over to air injection. As an extraction system, the system would extract hydrocarbon-rich gas from the soil, allowing additional hydrocarbons to volatilize, and drawing in additional oxygen from surrounding soil. The influx of oxygen will stimulate microbial degradation of hydrocarbons in the unsaturated zone, and likely increase the oxygen flux across the water table. As an injection system, a bioventing system would inject air (with approximately 21 percent oxygen) at relatively low flow rates to stimulate additional biodegradation of the fuel residuals. This system also increases the flux of oxygen across the water table, adding oxygen to the ground water and stimulating biodegradation of fuel residuals below the water table. Whether the system is extracting or injecting air, BTEX compounds are preferentially removed because of their greater volatility and mobility compared to other fuel constituents. In addition, soil near and below the water table will be treated during periods when the water table is low.

Results of an evaluation of bioventing systems at 57 sites (Engineering-Science, Inc., 1994b) indicate that TPH degradation rates range from less than 300 to greater than 9,000 milligrams TPH per kilogram of soil per year (mg/kg/year), with rates at most sites exceeding 1,000 mg/kg/year. A closer look at BTEX removal rates at 16 of these sites shows that after 1 year of bioventing, average BTEX concentrations in soil were reduced by 91 percent (for benzene) to greater than 99 percent (for ethylbenzene and xylenes) (Engineering-Science, Inc., 1994b). During the same 1-year period, soil TPH concentrations were reduced by an average of 70 percent, confirming that the BTEX compounds are preferentially removed.

On the basis of this information, model MAD_C was set up to reflect source removal. As a starting assumption, this model assumed that after 1 year of bioventing system operation, 50 percent of the soil BTEX would be removed. After the second year of operation, the model set-up assumed that an additional 25 percent of the BTEX would removed. After the third year of operation, it was assumed that steady-state conditions would be reached, with 10 percent of the BTEX remaining. To simulate the effects of BTEX reduction on dissolved BTEX concentrations, it was assumed that reductions in soil concentrations produced similar reductions in the BTEX loading rates. For example, at the beginning of the second predictive year of the MAD_C simulation (year 4 of the total simulation), the loading rates at each injection well were reduced to 50 percent of the calibrated model rates to simulate the effects of 1 year of bioventing. For the third predictive year the loading rates were decreased to 25 percent of the original values, and

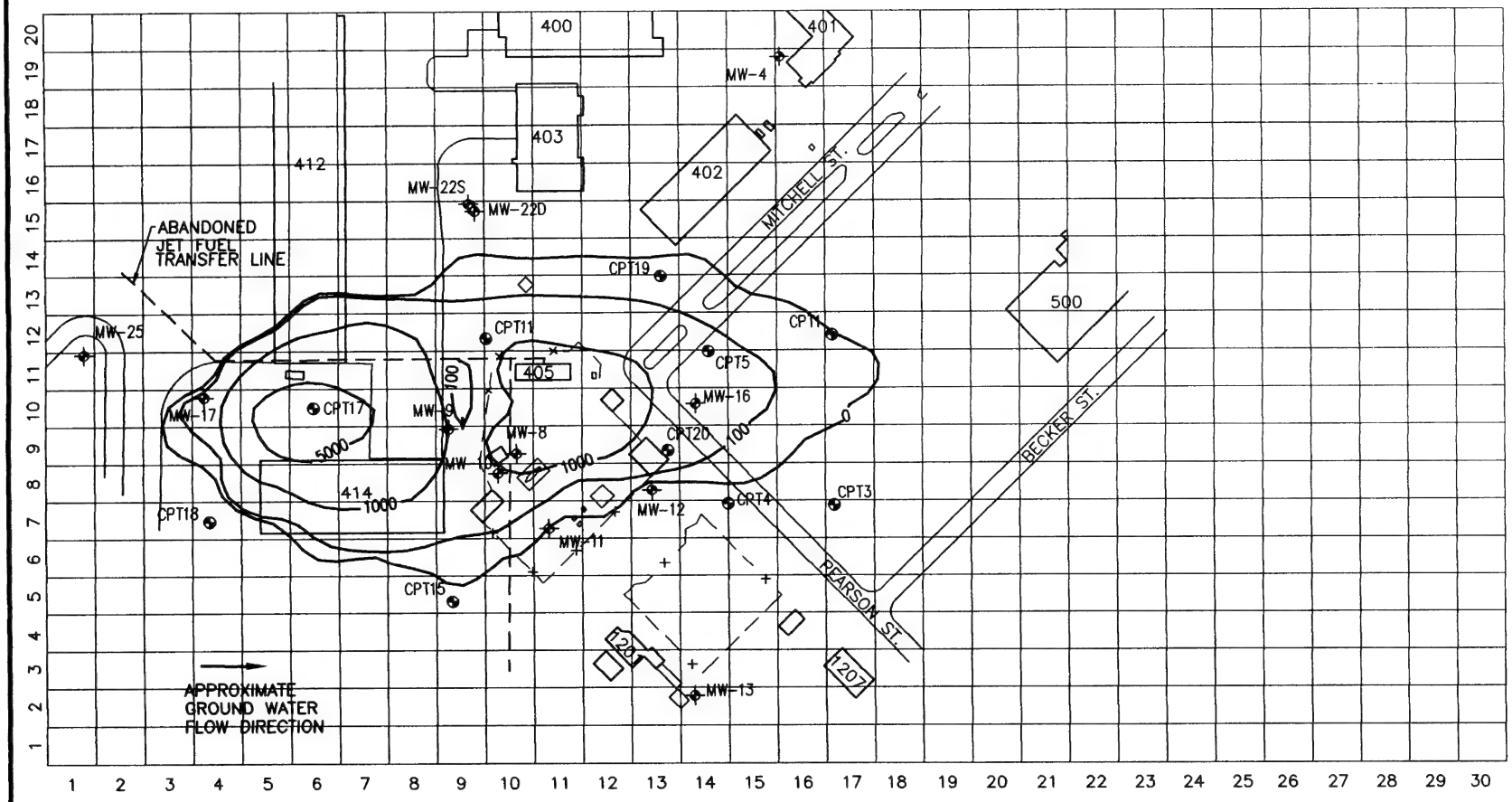
in the fourth and all subsequent years the loading rates were left at 10 percent of the original rates. While it is difficult to quantify the actual decrease in the BTEX loading rates that will be brought about by bioventing, a model based on these assumptions can provide an indication of the potential effects of source reduction.

Like MAD_B, this simulation was run to predict BTEX transport for 30 years beyond the calibrated model ending time. Figures 5.13, 5.14, and 5.15 show the results of this model 3, 7, and 30 years after source reduction begins, respectively. Results for this casesuggest that dissolved BTEX concentrations will decrease rapidly in the source areas, and the plume will gradually shrink until reaching a steady-state configuration in the vicinity of the Building 412 source area.

Figure 5.13 shows the computed plume configuration 3 years after source removal begins, or after 6 years of total simulation time. The highest simulated BTEX concentration in the Building 412 area is about 8,700 µg/L, while the maximum concentration in the POL source area is about 1,600 µg/L. The plume extent predicted for this time step is similar to that observed in 1994. Figure 5.14 shows the computed plume configuration 7 years after source removal begins, or after 10 years of total simulation time. For this case, the computed BTEX plume is approximately 100 feet longer than the observed plume, but it is narrower. In addition, the maximum BTEX concentrations in the Building 412 and POL source areas have decreased to 2,200 µg/L and 190 µg/L, respectively. After this point, the BTEX plume front begins to retreat toward the source areas, and about 20 years after source removal begins, the BTEX plume begins to stabilize. Figure 5.15 shows the plume configuration 30 years after source removal begins. Dissolved BTEX compounds are only present in the vicinity of the Building 412 source area, with a maximum concentration of about 2,000 µg/L.

5.7 CONCLUSIONS AND DISCUSSION

The results of two Bioplume II model scenarios for the Truax Field site suggest that the dissolved BTEX plume front is not likely to migrate more than 250 feet downgradient from its September 1994 position. The first scenario, model MAD_B, assumed that conditions that produced the calibrated model would remain constant for the full duration of the simulation. The second scenario, model MAD_C, assumed that BTEX loading rates would be reduced via bioventing or some other remedial action. MAD_B results suggest that within 10 years the BTEX plume will reach its maximum extent before



LEGEND

- MW-4 ⊕ MONITORING WELL LOCATION
- CPT1 ⊕ GROUND WATER MONITORING POINT
- —×— FENCE
- 402 BUILDING
- —5000— LINE OF EQUAL SIMULATED BTEX CONCENTRATION (μg/L)
  CONTOUR INTERVAL = VARIABLE

FIGURE 5.13

PREDICTED BTEX PLUME AFTER 3 YEARS MODEL MAD_C (WITH SOURCE REDUCTION)

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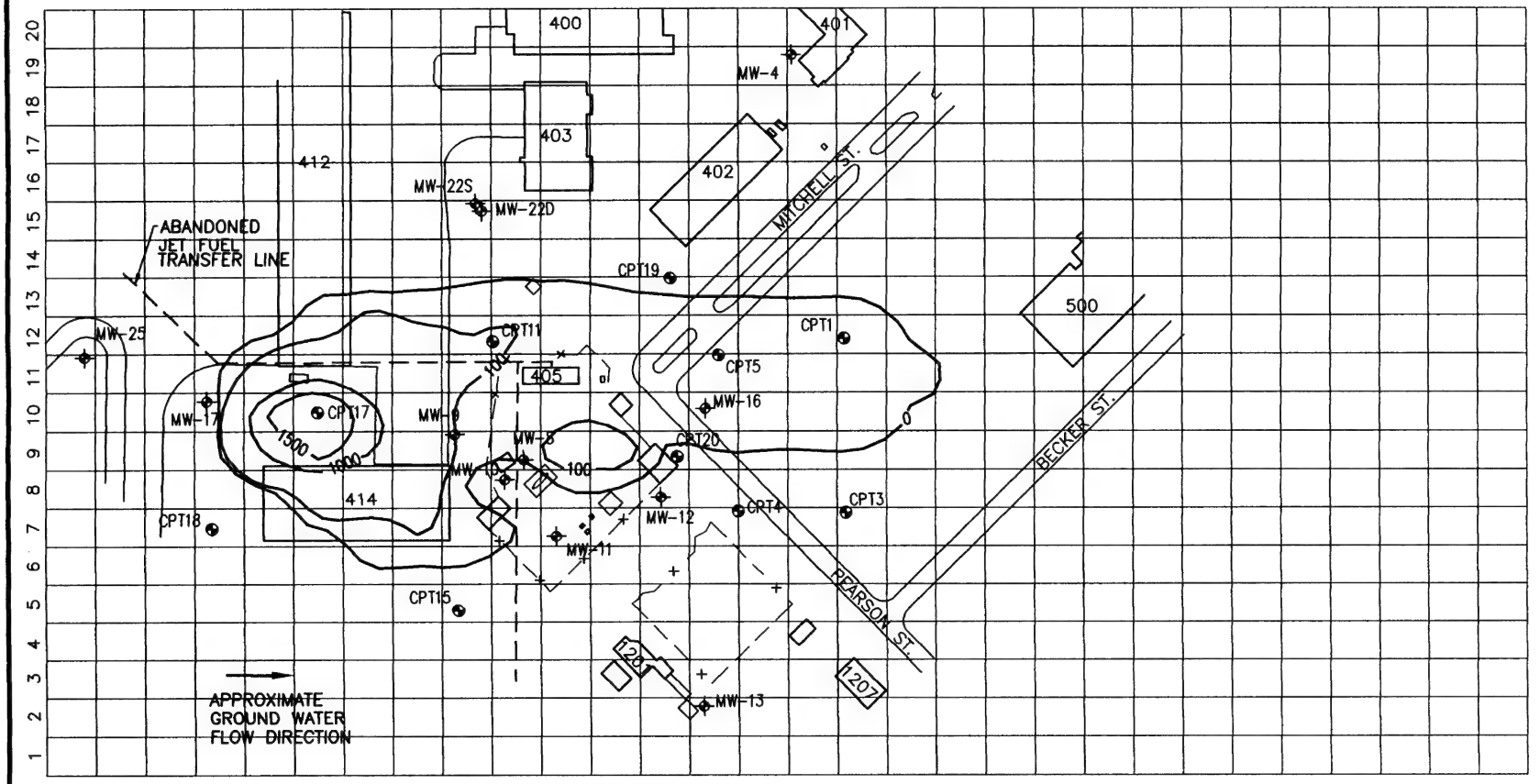

LEGEND

- MW-4 — MONITORING WELL LOCATION
- CPT1 — GROUND WATER MONITORING POINT
- —×— FENCE
- 402 — BUILDING
- —5000— LINE OF EQUAL SIMULATED BTEX CONCENTRATION (µg/L)
  CONTOUR INTERVAL = VARIABLE

FIGURE 5.14

PREDICTED BTEX PLUME AFTER 7 YEARS MODEL MAD_C (WITH SOURCE REDUCTION)

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Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

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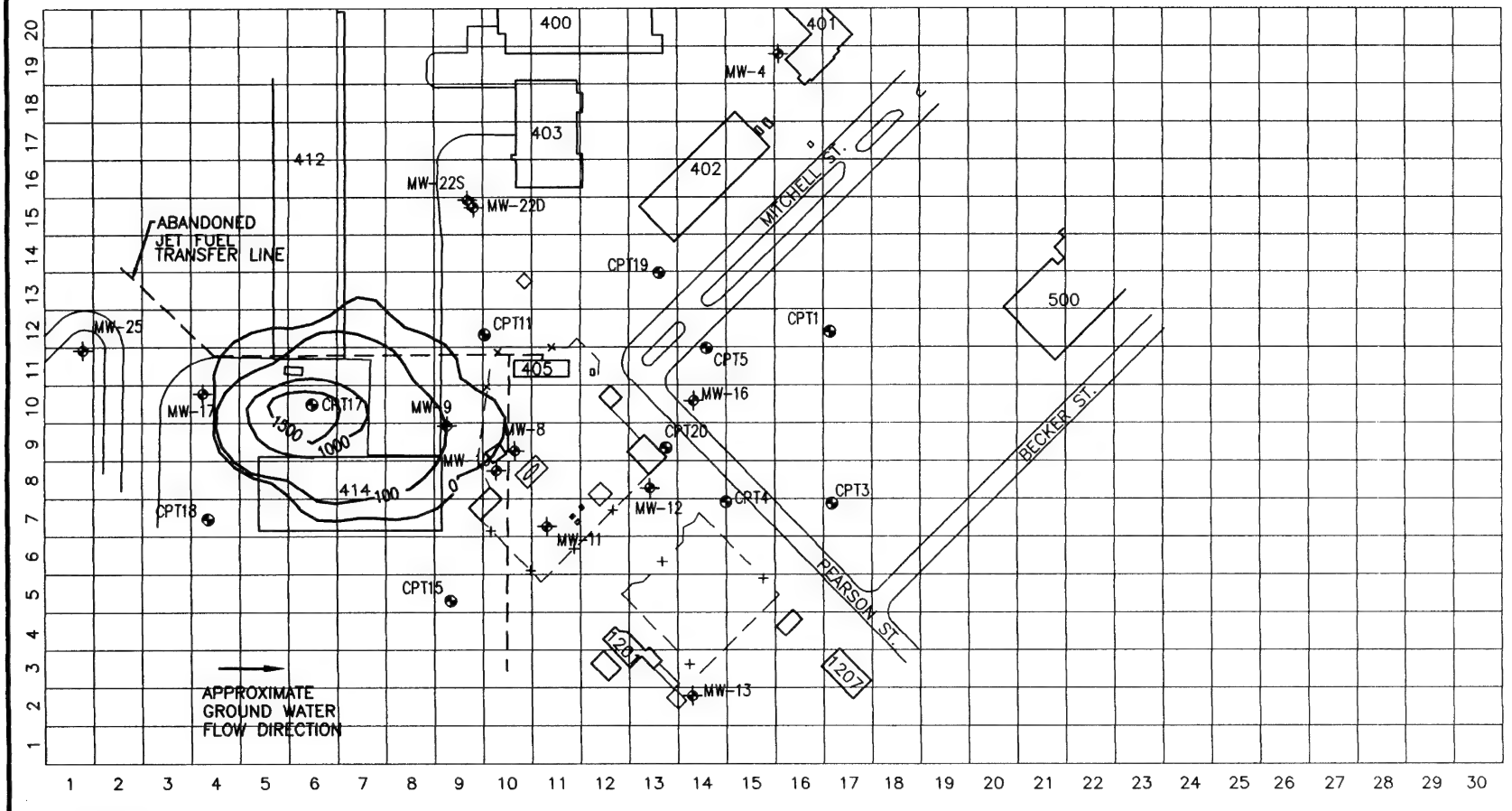

LEGEND

MW-4 ⊕ MONITORING WELL LOCATION

CPT1 ⊕ GROUND WATER MONITORING POINT

—×— FENCE

402 BUILDING

—5000— LINE OF EQUAL SIMULATED BTEX CONCENTRATION (µg/L)
CONTOUR INTERVAL = VARIABLE

0 150 300
FEET

FIGURE 5.15

PREDICTED BTEX PLUME AFTER 30 YEARS MODEL MAD_C (WITH SOURCE REDUCTION)

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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stabilizing. MAD_C results suggest that after source reduction, the BTEX plume front will migrate approximately 100 feet beyond the observed front before the plume begins to shrink back towards the source areas.

The rapid removal of BTEX compounds predicted by the simulations is largely a function of anaerobic biodegradation and sorption. However, the moderately high hydraulic conductivity of the sandy shallow aquifer enhances biodegradation by flushing water containing DO and other electron acceptors through the BTEX plume, which is retarded with respect to the advective ground water velocity. As a result, aerobic and anaerobic biodegradation is increased due to the continuous influx of electron acceptors. This is further enhanced by the additional influxes of electron acceptors in the grassy areas where runoff is concentrated and recharged to the ground water.

Bioplume II does not account for desorption of contaminants from the aquifer matrix. However, a review of mass-balance computations for models MAD_B and MAD_C indicates that the mass of BTEX sorbed onto the aquifer solids is at most 2.4 percent of the total dissolved mass that is removed by natural attenuation mechanisms. As a result, the concentrations of BTEX that will desorb after the aqueous plume diminishes will be very low compared to observed concentrations. In addition, as the compounds reenter the aqueous phase, they will be diluted and will be available for biodegradation.

In all cases, model simulations are conservative for several reasons, including:

1) Aerobic respiration, denitrification, iron reduction, sulfate reduction, and methanogenesis are all occurring at this site; however, only DO is considered as an electron acceptor during model simulations, and the anaerobic decay coefficient used in the calibrated model is lower than common literature values;

2) The stoichiometry used to determine the ratio between DO and total BTEX assumed that no microbial cell mass was produced during the reaction. As discussed in Section 4.3.2.1, this approach may be too conservative by a factor of three.

3) The highest DO concentration observed at the site was 7.19 mg/L. The highest simulated DO concentration upgradient of the source area (and therefore interacting with the core of the plume) in the simulations was 2.0

mg/L. Simulated DO concentrations toward the crossgradient margins of the plume were higher (based on field evidence), but this would not limit the modeled plume migration downgradient from the source areas.

Dissolved oxygen was also introduced through injection wells in and around the plume (on the basis of empirical evidence), but the areas of injection were relatively small compared to the overall plume area.

4) A midrange coefficient of retardation for benzene (2.06) was used for model simulations. Minimum coefficient of retardation values for the other BTEX compounds range from 1.42 to 3.50. The use of the low coefficient of retardation tends to increase the distance traveled by the simulated BTEX plume, but may provide a more accurate estimate of benzene transport.

5) Model MAD_B does not take into account source reduction already accomplished through excavation of soil south of Building 412. While residual contamination is probably present below the water table in that area, BTEX loading rates should decrease due to the removal of contaminated soil in the unsaturated zone.

The degradation and stabilization of the BTEX plumes observed in simulations MAD_B and MAD_C is feasible, given the observed BTEX concentrations, the conservative assumptions made in constructing the simulation, and the strong geochemical evidence of aerobic and anaerobic biodegradation. Models MAD_B and MAD_C represent two endpoints in a continuum of probable scenarios at this site. MAD_B is a "worst-case" scenario in that it assumes BTEX dissolution into the aquifer will continue indefinitely at the same rates, while the rates should actually decrease due to partial source remediation, weathering and degradation of the residual soil contamination, and continuing dissolution of BTEX from the source area. Model MAD_C is a more optimistic prediction which assumes that additional source remediation can rapidly reduce BTEX partitioning into the dissolved phase. It is likely that future site conditions will fall somewhere between those indicated by these two simulations.

SECTION 6

COMPARATIVE ANALYSIS OF REMEDIAL ALTERNATIVES

This section presents the development and comparative analysis of two ground water remedial alternatives for the Truax Field ANGB site. The intent of this evaluation is to determine if intrinsic remediation is an appropriate and cost-effective remedial technology to consider when developing final remedial strategies for the site, especially when combined with other innovative and conventional remedial technologies

Section 6.1 presents the evaluation criteria used to evaluate ground water remedial alternatives. Section 6.2 discusses the development of remedial alternatives considered as part of this demonstration project. Section 6.3 provides a brief description of each of these remedial alternatives. Section 6.4 provides a more detailed analysis of the remedial alternatives using the defined remedial alternative evaluation criteria. The results of this evaluation process are summarized in Section 6.5.

6.1 REMEDIAL ALTERNATIVE EVALUATION CRITERIA

The evaluation criteria used to identify appropriate remedial alternatives for shallow ground water contamination at the site were adapted from those recommended by the EPA (1988) for selecting remedies for Superfund sites (OSWER Directive 9355.3-01). These criteria included (1) long-term effectiveness and permanence, (2) technical and administrative implementability, and (3) relative cost. The following sections briefly describe the scope and purpose of each evaluation criterion. This report focuses on the potential use of intrinsic remediation and source reduction technologies to reduce BTEX concentrations within the shallow ground water to levels that meet regulatory action levels.

6.1.1 Long-Term Effectiveness and Permanence

Each remedial technology or remedial alternative (which can be a combination of remedial technologies such as intrinsic remediation and institutional controls) was analyzed to determine how effectively it will minimize ground water plume expansion so that ground water quality

standards can be achieved at a downgradient POC. The expected technical effectiveness based on case histories from other sites with similar conditions is also evaluated. The ability to minimize potential impacts to surrounding facilities and operations is considered. Also, the ability of each remedial alternative to protect both current and potential future receptors from potential risks associated with site-related contamination in shallow ground water is qualitatively assessed by conservatively estimating if a potential exposure pathway involving ground water could be completed, either now or in the future. This evaluation criterion also included permanence and the ability to reduce contaminant mass, toxicity, and volume. Time to implementation and time until protection is achieved are described. Long-term reliability for providing continued protection, including an assessment of potential for failure of the technology and the potential threats resulting from such a failure, is also evaluated.

6.1.2 Implementability

The technical implementation of each remedial technology or remedial alternative was evaluated in terms of technical feasibility and availability. Potential shortcomings and difficulties in construction, operations, and monitoring are presented and weighed against perceived benefits. Requirements for any post-implementation site controls such as LTM and land use restrictions are described. Details on administrative feasibility in terms of the likelihood of public acceptance and the ability to obtain necessary approvals are discussed.

6.1.3 Cost

The total cost (present worth) of each remedial alternative was estimated for relative comparison. An estimate of capital costs, and operations and post-implementation costs for site monitoring and controls is included. An annual inflation factor of 5 percent was assumed in present worth calculations.

6.2 FACTORS INFLUENCING ALTERNATIVES DEVELOPMENT

Several factors were considered during the identification and screening of remedial technologies for addressing shallow ground water contamination at the site. Factors considered included the objectives of the natural attenuation demonstration program; contaminant, ground water, and soil properties; present and future land use; and potential exposure pathways. The following section briefly describes each of these factors and how they were used to narrow the

list of potentially applicable remedial technologies to the final remedial alternatives considered for the site.

6.2.1 Program Objectives

The intent of the intrinsic remediation demonstration program sponsored by AFCEE is to develop a systematic process for scientifically investigating and documenting naturally occurring subsurface attenuation processes that can be factored into overall site remediation plans. The objective of this program and the specific Truax Field study is to provide solid evidence of intrinsic remediation of dissolved fuel hydrocarbons so that this information can be used to develop an effective ground water remediation strategy. A secondary goal of this multi-site initiative is to provide a series of regional case studies that demonstrate that natural processes of contaminant degradation can often reduce contaminant concentrations in ground water to below acceptable cleanup standards before completion of potential exposure pathways.

Because the objective of this program is to study natural processes in the saturated zone rather than all contaminated media (soil, soil gas, etc.), technologies have been evaluated based primarily on their potential impact on shallow ground water and phreatic soils. Technologies that can reduce vadose zone contamination and partitioning of contaminants into ground water have also been evaluated. Many of the source removal technologies evaluated in this section will also reduce soil and soil gas contamination, but it is important to emphasize that the remedial alternatives developed in this document are not intended to remediate all contaminated media. Additional program objectives set forth by AFCEE include cost effectiveness and minimization of waste. Technologies that may meet these criteria include institutional controls, soil vapor extraction, bioventing, biosparging, ground water pump and treat, and intrinsic remediation. Soil excavation, slurry walls, sheet piling, carbon adsorption, *ex situ* biological or chemical treatment, and onsite/offsite disposal are not attractive technology candidates for this site.

6.2.2 Contaminant Properties

The site-related contaminants considered as part of this demonstration at the Truax Field site are the BTEX compounds. The source of this contamination is weathered petroleum (i.e., JP-4 fuel) present as residual contamination in capillary fringe and saturated soil in the vicinity of Building 412 and the POL yard. The physiochemical characteristics of JP-4 and the individual BTEX compounds will greatly influence the effectiveness and selection of a remedial technology.

Petroleum hydrocarbon mixtures, such as JP-4, are composed of over 300 compounds with different physiochemical characteristics. JP-4 is classified as an LNAPL with a liquid density of 0.75 gram per cubic centimeter (g/cc) at 20 °C (Smith *et al.*, 1981). Many compounds in JP-4 sorb very well to soil and are concentrated in the capillary fringe because the mixture is less dense than water. JP-4 is slightly soluble in water, with a maximum solubility of approximately 300 mg/L. JP-4 is also a primary substrate for biological metabolism. Simultaneous biodegradation of aliphatic, aromatic, and alicyclic hydrocarbons has been observed. In fact, mineralization rates of hydrocarbons in mixtures such as JP-4 may be faster than mineralization of the individual constituents as a result of cometabolic pathways (Jamison *et al.*, 1975; Perry, 1984).

The BTEX compounds are generally volatile, highly soluble in water, and adsorb less strongly to soil than other hydrocarbons in a petroleum mixture. These characteristics allow the BTEX compounds to leach more rapidly from contaminated soil into ground water, and to migrate as dissolved contamination (Lyman *et al.*, 1992). All of the BTEX compounds are highly amenable to *in situ* degradation by both biotic and abiotic mechanisms.

Benzene is very volatile, with a vapor pressure of 76 millimeters of mercury (mm Hg) at 20°C and a Henry's Law Constant of approximately 0.0054 atmosphere-cubic meters per mole (atm-m^3/mol) at 25°C (Hine and Mookerjee, 1975; Jury *et al.*, 1984). The solubility of pure benzene in water at 20°C has been reported to be 1,780 mg/L (Verschueren, 1983). Benzene is normally biodegraded to carbon dioxide, with catechol as a short-lived intermediate (Hopper, 1978; Ribbons and Eaton, 1992).

Toluene is also volatile, with a vapor pressure of 22 mm Hg at 20°C and a Henry's Law Constant of about 0.0067 atm-m^3/mol at 25°C (Pankow and Rosen, 1988; Hine and Mookerjee, 1975). Toluene sorbs more readily to soil media relative to benzene, but still is very mobile. The solubility of pure toluene in water at 20°C is approximately 515 mg/L at 20°C (Verschueren, 1983). Toluene has been shown to degrade to pyruvate, caetaldehyde, and completely to carbon dioxide via the intermediate catechol (Hopper, 1978; Wilson *et al.*, 1986; Ribbons and Eaton, 1992).

Ethylbenzene has a vapor pressure of 7 mm Hg at 20°C and a Henry's Law Constant of 0.0066 atm-m^3/mol (Pankow and Rosen, 1988; Valsaraj, 1988). Ethylbenzene sorbs more strongly to soils than benzene but less strongly than toluene (Abdul *et al.*, 1987). Pure ethylbenzene is also less soluble than benzene and toluene in water at 152 mg/L at 20°C (Verschueren, 1983; Miller

et al., 1985). Ethylbenzene ultimately degrades to carbon dioxide via its intermediate 3-ethylcatechol (Hopper, 1978; Ribbons and Eaton, 1992).

The three isomers of xylene have vapor pressures ranging from 7 to 9 mm Hg at 20°C and Henry's Law Constants of between 0.005 and 0.007 atm-m^3/mol at 25°C (Mackay and Wolkoff, 1973; Hine and Mookerjee, 1975; Pankow and Rosen, 1988). Of all of the BTEX compounds, xylenes sorb most strongly to soil, but still can leach from soil into the ground water (Abdul *et al.*, 1987). Pure xylenes have water solubilities of 152 to 160 mg/L at 20°C (Bohon and Claussen, 1951; Mackay and Shiu, 1981; Isnard and Lambert, 1988). Xylenes can degrade to carbon dioxide via pyruvate carbonyl intermediates (Hopper, 1978; Ribbons and Eaton, 1992).

On the basis of these physiochemical characteristics, intrinsic remediation, soil vapor extraction, bioventing, biosparging, ground water extraction, and air stripping technologies could all be effective options for collecting, destroying, and/or treating BTEX contaminants at the Truax Field site.

6.2.3 Site-Specific Conditions

Two general categories of site-specific characteristics were considered when identifying remedial technologies for comparative evaluation as part of this demonstration project. The first category was physical characteristics such as ground water depth, gradient, flow direction, and soil type, which influence the types of remedial technologies most appropriate for the site. The second category involved assumptions about future land use and potential exposure pathways. Each of these site-specific characteristics have influenced the selection of remedial alternatives included in the comparative evaluation. Another factor to consider is that highly contaminated unsaturated soil from the area south of Building 412 has already been excavated and thermally treated.

6.2.3.1 Ground Water and Soil Characteristics

Site geology and hydrogeology will have a profound effect on the transport of contaminants and the effectiveness and scope of required remedial technologies at a given site. Hydraulic conductivity is perhaps the most important aquifer parameter governing ground water flow and contaminant transport in the subsurface. The velocity of the ground water and dissolved contamination is directly related to the hydraulic conductivity of the saturated zone. Slug testing conducted in the vicinity of the site indicate a moderately high conductivity within the sand unit

present in the vicinity of the source area and dissolved plume. Estimated conductivity values ranged from 6.5×10^{-3} to 2.2×10^{-2} ft/min, characteristic of sand or silty sand. The hydraulic conductivity at this site directly influences the fate and transport of contaminants. The shallow ground water has migrated relatively rapidly, increasing the extent of contamination (i.e., the plume has expanded) but decreasing the average concentration within the aquifer through dilution and biodegradation.

Although high hydraulic conductivity can result in plume expansion and migration, this same characteristic will also enhance the effectiveness of other remedial technologies, such as ground water extraction, biosparging, and intrinsic remediation. For example, it should be less expensive and time-consuming to capture and treat the contaminant plume using a network of extraction wells in areas of high hydraulic conductivity. Contaminant recovery may also be maximized when contaminants are not significantly sorbed to and retarded by phreatic soil. The effectiveness of biosparging may also be increased in highly conductive aquifers because of reduced entry pressures and increased radius of influence. Greater hydraulic conductivity would also increase the amount of contaminant mass traveling through a biosparging network. The DO introduced through biosparging can also enhance aerobic degradation of the dissolved contaminant mass.

The movement of contaminants within the subsurface away from the source will also increase the effectiveness of natural biodegradation processes by distributing the contaminant mass into areas enriched with electron acceptors. In addition, the because BTEX compounds are retarded relative to the advective flow velocity, relatively fresh ground water containing DO and other electron acceptors will migrate through the plume area, further increasing biodegradation.

To satisfy the requirements of indigenous microbial activity and intrinsic remediation, the aquifer must also provide an adequate and available carbon or energy source, electron acceptors, essential nutrients, proper ranges of pH, temperature, and redox potential. Data collected as part of the field work phase of this demonstration project and described in Sections 3 and 4 of this document indicate that this site is characterized by adequate and available carbon/energy sources and electron acceptors to support measurable biodegradation of fuel hydrocarbon contamination by indigenous microorganisms. DO, nitrate, ferric iron, sulfate, and carbon dioxide (which is utilized during methanogenesis) represent sources of electron acceptor capacity for the biodegradation of BTEX compounds at the site. Further, because fuel hydrocarbon-degrading microorganisms have been known to thrive under a wide range of temperature and pH conditions (Freeze and Cherry, 1979), the physical and chemical conditions of the ground water and phreatic soil at the site are not likely to inhibit microorganism growth.

Fuel hydrocarbon-degrading microorganisms are ubiquitous, and as many as 28 hydrocarbon-degrading isolates (bacteria and fungi) have been discovered in different soil environments (Davies and Westlake, 1977; Jones and Eddington, 1968). Indigenous microorganisms have a distinct advantage over microorganisms injected into the subsurface to enhance biodegradation because indigenous microorganisms are well adapted to the physical and chemical conditions of the subsurface in which they reside (Goldstein *et al.*, 1985). Microbe addition was not considered a viable remedial technology for this site.

6.2.3.2 Potential Exposure Pathways

A pathways analysis identifies the potential human and ecological receptors that could potentially come into contact with site-related contamination and the pathways through which these receptors might be exposed. To have a completed exposure pathway, there must be a source of contamination, a potential mechanism(s) of release, a pathway of transport to an exposure point, an exposure point, and a receptor. If any of these elements do not exist, the exposure pathway is considered incomplete, and receptors will not come into contact with site-related contamination. Evaluation of the potential long-term effectiveness of any remedial technology or remedial alternative as part of this demonstration project includes determining if the approach will be sufficient and adequate to minimize plume expansion so that potential exposure pathways involving shallow ground water are incomplete.

Assumptions about current and future land uses at a site form the basis for identifying potential receptors, potential exposure pathways, reasonable exposure scenarios, and appropriate remediation goals. EPA (1991) advises that the land use associated with the highest (most conservative) potential level of exposure and risk that can reasonably be expected to occur should be used to guide the identification of potential exposure pathways and to determine the level to which the site must be remediated. The source areas consist of the POL yard facilities and a former jet fuel distribution line south of Building 412. A bulk fuel receiving system, fuel dispensers, and five USTs are present within the POL yard.

The Building 412 source area is bounded by taxiways and the airport infields to the northwest, and to the south and northeast by aircraft hangars and maintenance facilities. The POL yard is immediately southeast of the Building 412 source area. Hangars, maintenance buildings, aircraft pads, taxiways, and runway infields are located to the west, south, and north of the POL yard. Immediately southeast of the POL yard is a parking lot, and further in that direction are Buildings 500 and 510. The ground water plume originating from the source areas is migrating

to the southeast, and has impacted ground water in an area extending from the vicinity of Buildings 412 and 414 and just beneath the parking lot, in the area bounded by Mitchell Street, Pearson Street, Becker Street, and Building 500 (Figure 4.2). Further to the southeast across Hoffman Street is additional base property, and beyond that are a variety of commercial and/or light industrial properties. Thus, the current land use within and downgradient of the contaminant plume is entirely industrial.

Under reasonable current land use assumptions, potential receptors only include worker populations. Workers could be exposed to site-related contamination in phreatic soils or shallow ground water if these materials are removed or exposed during future construction excavations or remedial activities. Ground water from the shallow aquifer is not currently used to meet any demands at Truax Field. On-Base water demands are met by municipal supply wells screened in the deep bedrock aquifer. Exposure pathways involving other environmental media such as shallow soils and soil gas in the source area were not considered as part of this project, but should be considered in overall site remediation decisions.

Assumptions about hypothetical future land uses must also be made to ensure that the remedial technology or alternative considered for shallow ground water at the site is adequate and sufficient to provide long-term protection. No changes in land use are anticipated in the foreseeable future, so an industrial land use assumption is most appropriate. Thus, potential future receptors include only worker populations. The potential future exposure pathways involving workers are identical to those under current conditions provided shallow ground water is not used to meet industrial water demands. In summary, the use of the intrinsic remediation technology at this site will require that the source area be maintained as industrial property and that restrictions on shallow ground water use be enforced in areas downgradient of the site until natural attenuation reduces contaminants to levels that pose no risk. If source removal technologies such as soil vapor extraction, bioventing, biosparging, or ground water pump and treat are implemented, they will have some impact on the short- and long-term land use options and will require some level of institutional control and worker protection during remediation.

6.2.3.3 Remediation Goals for Shallow Ground Water

Model results suggest that BTEX compounds are not likely to move more that 250 feet downgradient of the observed plume front. Therefore, an area approximately 250 feet beyond the plume boundary observed in September 1994 has been identified as the point of compliance (POC) for ground water remedial activities because this appears to be the maximum extent of

future contaminant migration. This is a suitable location for monitoring and for demonstrating compliance with protective ground water quality standards, such as promulgated ground water maximum contaminant levels (MCLs).

This remedial strategy assumes that compliance with promulgated, single-point remediation goals is not necessary if site-related contamination does not pose a threat to human health or the environment (i.e., the exposure pathway is incomplete). Thus, the magnitude of required remediation in areas that can and will be placed under institutional control is different from the remediation that is required in areas that may be available for unrestricted use. The primary RAO for shallow ground water within and downgradient of the Truax Field site is limited plume expansion to prevent exposure of downgradient receptors to concentrations of BTEX in ground water at levels that exceed regulatory standards. This means that viable remedial alternatives must be able to achieve concentrations that minimize plume migration and/or expansion. The RAO for shallow ground water at the POC is attainment of state Enforcement Standards (ESs) listed in Table 6.1 for each of the BTEX compounds. Although it is unlikely that ground water would be ingested by humans, this level of long-term protection is appropriate.

TABLE 6.1

POINT-OF-COMPLIANCE REMEDIATION GOALS
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Compound	Wisconsin ESs (µg/L)
Benzene	5
Toluene	343
Ethylbenzene	1,360
Total Xylenes	620

In summary, available data suggest that there is no complete potential exposure pathway involving shallow ground water under current conditions. Moreover, it is likely that no potential exposure pathways involving shallow ground water would be complete under future land use assumptions, provided use of shallow ground water as a potable or industrial source of water is

prohibited by institutional controls within the plume area and within an area approximately 250 feet downgradient of the 1994 plume front. Thus, institutional controls are likely to be a necessary component of any ground water remediation strategy for this site. The required duration of these institutional controls may vary depending on the effectiveness of the selected remedial technology at reducing contaminant mass and concentration in the ground water.

6.2.4 Summary of Remedial Technology Screening

Several remedial technologies have been identified and screened for use in treating the shallow ground water at the site. Table 6.2 identifies the initial remedial technologies considered as part of this demonstration and those retained for detailed comparative analysis. Screening was conducted systematically by considering the program objectives of the AFCEE intrinsic remediation demonstration, physiochemical properties of the BTEX compounds, and other site-specific characteristics such as hydrogeology, land use assumptions, potential exposure pathways, and appropriate remediation goals. All of these factors will influence the technical effectiveness, implementation, and relative cost of technologies for remediating shallow ground water underlying and migrating from the site. The remedial technologies retained for development of remedial alternatives and comparative analysis include institutional controls, intrinsic remediation, LTM, bioventing, and biosparging.

Technologies incorporating ground water extraction, though implementable, were not retained for further consideration. In light of the evidence for the effectiveness of natural attenuation processes at this site (and the evidence for increased effectiveness if additional source reduction is implemented), ground water extraction and/or treatment systems would not meet the AFCEE program objectives of cost effectiveness and waste minimization.

6.3 BRIEF DESCRIPTION OF REMEDIAL ALTERNATIVES

This section describes how remedial technologies retained from the screening process were combined into two remedial alternatives for the Truax Field site. Sufficient information on each remedial alternative is provided to facilitate a comparative analysis of effectiveness, implementability, and cost in Section 6.4.

TABLE 6.2
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF
TECHNOLOGIES AND PROCESS OPTIONS FOR GROUND WATER REMEDIATION
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

General Response Action	Technology Type	Process Option	Implementability	Retain
Long-Term Monitoring	Periodic Ground Water Monitoring	Confirmation Wells	Many existing wells are available to confirm the progress of remediation.	Yes
		Point-of-Compliance Wells	Sufficient distance exists between the plume and point-of-compliance to locate several wells.	Yes
Institutional Controls	Ground Water Use Control	Land Use Control/Regulate Well Permits	Plume area is currently within the base boundary and land use and ground water use are under base jurisdiction.	Yes
		Seal/Abandon Existing Wells	No production wells are known to exist in the existing or predicted plume area.	No
		Point-of-Use Treatment	No shallow ground water is extracted from the plume area for any use.	No
	Public Education	Meetings/ Newsletters	Base public relations and environmental management offices have many information avenues to workers and residents.	Yes
Containment of Plume	Hydraulic Controls	Passive Drain Collection	No likely receptors downgradient of site. Installation could disrupt base operations. Hydraulic conductivity of site soils favors pumping.	No
		Minimum Pumping/Gradient Control	Hydraulic conductivities of site soils are relatively high and would allow extraction of sufficient volumes. Treatment of extracted water would probably be necessary. No likely receptors downgradient of site.	No
	Physical Controls	Slurry Walls/Grout Curtains	Requires significant disruption of base operating area. Limited effectiveness.	No
		Sheet Piling	Requires significant disruption of base operating area. Limited effectiveness.	No
	Reactive/Semi-Permeable Barriers	Biologically Active Zones	Natural biodegradation of BTEX compounds can be stimulated by allowing contaminated ground water to flow through an aquifer zone which has enhanced oxygen and nutrient conditions. A new, unproven technology.	No

TABLE 6.2 (Continued)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF
TECHNOLOGIES AND PROCESS OPTIONS FOR GROUND WATER REMEDIATION
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

General Response Action	Technology Type	Process Option	Implementability	Retain
In Situ Treatment	Biological	Oxygen and/or Nutrient Enhanced Biodegradation (Biosparging)	Differs from biologically active zone in that oxygen and/or nutrients are injected downgradient of plume to limit plume migration by enhancing biodegradation and reducing BTEX concentrations as the plume moves downgradient from the source area.	Yes
	Chemical/Physical	Intrinsic Remediation	A combination of natural biological, chemical, and physical removal mechanisms which occur to varying degrees on every site. Ground water sampling at the Truax Field Site indicates that this is a major, ongoing remediation process.	Yes
		Air Sparging (Volatilization)	Injection of air into contaminated aquifer creating a mass transfer of BTEX into air bubbles and into vadose zone. Limited radius of influence and short-circuiting are common problems.	No
Aboveground Ground Water Treatment	Ground Water Extraction	Vertical Pumping Wells	Entire groundwater plume is pumped by installing numerous wells with submersible pumps. Option is implementable, but there are no likely receptors downgradient of site.	No
		Downgradient Horizontal Drains	See Passive Drain Collection.	No
	Biological	Bioreactors	High flow rates require excessive retention times and large reactors. BTEX is often volatilized in these systems.	No
	Chemical/Physical	Air Stripping	Cost-effective technology for removing varying concentrations of BTEX at higher flow rates. Ground water extraction unlikely.	No
		Activated Carbon	Cost prohibitive for more concentrated BTEX. Creates a carbon disposal problem. Carbon is also used to treat off-gas from air strippers.	No
		UV/Ozone Reactors	High flow rates require excessive retention times and large, expensive reactors.	No

TABLE 6.2 (Continued)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF
TECHNOLOGIES AND PROCESS OPTIONS FOR GROUND WATER REMEDIATION
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

General Response Action	Technology Type	Process Option	Implementability	Retain
Aboveground Treatment	Direct Discharge to Industrial Waste Water Treatment Plant (IWWTP)		Viable option when an IWWTP is readily available and capable of handling BTEX and hydraulic loading.	No
Treated Ground Water Disposal	Discharge to IWWTP or Sanitary Sewer	IWWTP	Viable option when access to sanitary sewer exists and hydraulic loading is acceptable. Ground water extraction is unlikely.	No
		Sanitary Sewer	Viable option when access to sanitary sewer exists and hydraulic loading is acceptable.	No
	Treated Ground Water Reinjection	Vertical Injection Wells	Not recommended due to clogging and high maintenance.	No
		Injection Trenches	Require large trenches and can be subject to injection well permitting.	No
	Discharge to Surface Waters	Storm Drains	Viable option but generally requires NPDES or other discharge permit. Ground water extraction is unlikely.	No
Source Removal/Soil Remediation	Excavation/ Treatment	Biological Landfarming	Excavation already carried out south of Building 412. Excavation in POL Yard is not feasible due to disruption of Base fueling operations.	No
		Thermal Desorption	This option was used for soils from the excavation south of Building 412 (Nine Springs, 1994). Excavation in POL Yard is not feasible.	No
	In Situ	Bioventing	Air injection to stimulate biodegradation of fuel residuals. Soils in source areas should not limit effectiveness.	Yes
		Soil Vapor Extraction	Vapor extraction has been successfully implemented at other sites. Requires source definition and off-gas treatment. Bioventing is preferred, but vapor extraction may be necessary before bioventing can be implemented.	Yes

6.3.1 Alternative 1 - Intrinsic Remediation and Institutional Controls with Long-Term Monitoring

Intrinsic remediation is achieved when naturally occurring attenuation mechanisms bring about a reduction in the total mass of a contaminant in the soil or dissolved in ground water. Intrinsic remediation results from the integration of several subsurface attenuation mechanisms that are classified as either destructive or nondestructive. Destructive attenuation mechanisms include biodegradation, abiotic oxidation, and hydrolysis. Nondestructive attenuation mechanisms include sorption, dilution (caused by dispersion and infiltration), and volatilization. In some cases, intrinsic remediation will reduce dissolved contaminant concentrations below numerical concentration goals intended to be protective of human health and the environment. As indicated by the existing evidence of intrinsic remediation described in Section 4, these processes are occurring in the vicinity of Building 412 and the POL yard and will continue to reduce contaminant mass in the plume area.

Results of model MAD_B suggest that the dissolved plume should reach its maximum extent within 10 years. After that time, the Bioplume II model predicts that intrinsic remediation within the BTEX plume and along the plume margins will prevent further plume migration, assuming BTEX loading in the source area remains constant. This plume could extend to a maximum of 250 feet downgradient of the plume front indicated by September 1994 data. This does not take into account source reduction through excavation south of Building 412 or weathering of the residual product trapped in the soil pores above and below the water table.

Implementation of Alternative 1 would require the use of institutional controls such as land use restrictions and LTM. Land use restrictions may include placing long-term restrictions on soil excavation within the source area and long-term restrictions on ground water well installations within and downgradient of the plume area. The intent of these restrictions would be to reduce potential receptor exposure to contaminants by legally restricting activities within areas affected by site-related contamination. Model scenarios MAD_B and MAD_C delineate the maximum and minimum estimated plume migration distances. Future plume migration and degradation will most likely result in conditions that fall between these limits. To be conservative, the results of model MAD_B should be considered in making decisions regarding ground water monitoring and potential land use restrictions.

As a minimum, ground water monitoring within the plume area would be conducted twice annually as part of this remedial technology to evaluate the progress of natural attenuation processes. Based on the potential plume migration suggested by model MAD_B, it is unlikely

that benzene concentrations exceeding the ES of 5 µg/L would be present more that 250 feet downgradient of the 1994 plume front (this would be true even if it were assumed that model contaminant concentrations are all benzene rather than total BTEX). Results of model MAD_C suggest that with source reduction, the BTEX plume would reach no more than 100 feet beyond the 1994 plume front.

Because there are no apparent downgradient receptors, three POC wells should be placed downgradient of the modeled maximum extent (i.e., more than 250 feet downgradient of the source area). In addition, four LTM wells within, upgradient, and immediately downgradient from the existing BTEX plume would be used to monitor the effectiveness of intrinsic remediation. LTM wells are further described in Section 7.2.1. Detection of benzene in excess of 5 µg/L at downgradient wells may require additional evaluation and modeling to assess BTEX migration and to determine the probable extent of BTEX migration, or to determine if additional corrective action would be necessary. Land use restrictions would also require reevaluation.

Public education on the selected alternative would be developed to inform Base personnel and residents of the scientific principles underlying source reduction and intrinsic remediation. This education could be accomplished through public meetings, presentations, press releases, and posting of signs where appropriate. Periodic site reviews could also be conducted every year using data collected from the long-term ground water monitoring program. The purpose of these periodic reviews would be to evaluate the extent of contamination, assess contaminant migration and attenuation through time, document the effectiveness of source removal and/or institutional controls at the site, and reevaluate the need for additional remedial actions at the site.

6.3.2 Alternative 2 - Bioventing, Biosparging, Intrinsic Remediation, and Institutional Controls with Long-Term Ground Water Monitoring

This alternative is identical to Alternative 1 except that bioventing would be used to enhance the biodegradation of organic contaminants in subsurface soils by supplying oxygen to indigenous microbes by using low-flow air injection in the vicinity of the POL Yard and Building 412. Although some soil has been excavated immediately south of Building 412, it appears likely that some contaminated soil remains beneath Building 412 and beneath the concrete pad immediately southeast of the remedial excavation. Bioventing is preferred over soil vapor extraction because bioventing uses a low rate of air injection that significantly reduces emissions into the atmosphere while maximizing *in situ* biodegradation.

Biosparging should be considered as an additional source removal mechanism. Bioventing and biosparging could easily be combined at this site by injecting air several feet below the ground water surface and allowing air (oxygen) to move upward through the capillary fringe and into the contaminated vadose zone. This combination of two technologies using a single air injection well at each location should be considered when designing a full-scale bioventing system. Biosparging would also increase the DO content of the ground water and promote more rapid degradation of BTEX compounds in the plume. On the basis of Parsons ES experience in the application bioventing/biosparging technologies, conditions at this site require the installation of about 20 air injection wells placed at 50-foot intervals (assuming a 35-foot radius of influence). Seven of the wells would be located in the vicinity of the south end of Building 412 and the northwestern margin of the concrete apron immediately downgradient from the remedial excavation. Thirteen wells would be placed in the POL Yard and in the area immediately north of the Yard.

As indicated in Section 5.6.2, it has been estimated that a bioventing system should remove at least 90 percent of residual soil BTEX compounds within 3 years. Simulation MAD_C assumed that such a decrease in soil concentrations will produce a similar decrease in BTEX dissolution into ground water. In this case, the predicted BTEX plume reaches its maximum extent (approximately 100 feet downgradient from the observed plume front) within 10 years. After reaching that extent, model MAD_C suggests that the combination of source reduction and natural attenuation causes the plume to rapidly shrink back to the source area in the vicinity of Building 412 before stabilizing.

As with Alternative 1, institutional controls and LTM would be required. POC and LTM wells would be installed in the same locations indicated in the previous section. Ground water monitoring would also follow the same schedule.

6.4 EVALUATION OF ALTERNATIVES

This section provides a comparative analysis of each of the remedial alternatives based on the effectiveness, implementability, and cost criteria. A summary of this evaluation is presented in Section 6.5.

6.4.1 Alternative 1 - Intrinsic Remediation and Institutional Controls with Long-Term Monitoring

6.4.1.1 Effectiveness

Section 5 of this document presents the results of the Bioplume II modeling completed to support the intrinsic remediation alternative at the Truax Field site. Two models (MAD_B and MAD_C) were used to illustrate the range of potential future conditions at the site. Model MAD_B predicted BTEX migration and degradation based on conditions that produced the calibrated model. Model MAD_C incorporated the effects of BTEX loading rates due to source reduction by bioventing/biosparging.

Model results predicted that natural attenuation mechanisms will significantly limit contaminant migration and reduce contaminant mass and toxicity. Benzene concentrations should not exceed the ES at the POC wells. The Bioplume II model is based upon numerous conservative assumptions. Ground water monitoring at the LTM and POC wells will ensure the protectiveness of this alternative. While this alternative would not cease to be protective if the benzene plume was intercepted by the POC wells, such an instance would indicate that site conditions should be reevaluated.

The effectiveness of this remedial alternative requires that excavations or drilling within the source area be conducted only by properly protected site workers. Reasonable land use assumptions for the plume area indicate that exposure is unlikely unless excavation or drilling activities bring saturated soil to the surface. Long-term land use restrictions will be required to ensure that shallow ground water will not be pumped or removed for potable use within, and approximately 500 feet in all directions from, the existing BTEX plume. Existing health and safety plans should be enforced to reduce risks from additional excavation or from installing and monitoring additional POC wells.

Compliance with program goals is one component of the long-term effectiveness evaluation criterion. Alternative 1 will satisfy program objectives designed to promote intrinsic remediation as a component of site remediation and to scientifically document naturally occurring processes. This alternative also satisfies program goals for cost effectiveness and waste minimization.

Alternative 1 is based on the effectiveness of enhanced naturally occurring processes that minimize contaminant migration and reduce contaminant mass over time, and the effectiveness of institutional controls. As described earlier, an investigation of the potential effectiveness of

naturally occurring processes at the Truax Field site using field data and the Bioplume II model demonstrated that the BTEX plume migration will be significantly limited. The model sensitivity analysis completed for this site (Section 5) suggests that even under the most conservative (i.e., worst-case) conditions, the naturally occurring processes at the site should reduce contaminant migration so that the maximum distance traveled by the plume is unlikely to be beyond the proposed POC wells.

Apart from the administrative concerns associated with enforcement of long-term land use restrictions and long-term ground water monitoring programs, this remedial alternative should provide reliable, continued protection. It is assumed for cost comparison purposes that dissolved benzene concentrations will exceed state ESs throughout the plume for approximately 15 years under Alternative 1. An additional 5 years of annual ground water monitoring will be required to ensure that intrinsic remediation has uniformly reduced all BTEX compounds to levels below state ESs.

6.4.1.2 Implementabilty

Alternative 1 is not technically difficult to implement. Installation of LTM and POC wells and annual ground water monitoring are standard procedures. Long-term management efforts will be required to ensure proper sampling procedures are followed. Periodic site reviews should be conducted to confirm the adequacy and completeness of LTM data and verify the effectiveness of this remediation approach. There may also be administrative concerns associated with long-term enforcement of ground water use restrictions. Future land use within the source area may be impacted by leaving contaminated soil and ground water in place. Regulators and the public will have to be informed of the benefits and limitations of the intrinsic remediation option. Educational programs are not difficult to implement, and the initial regulatory reaction to this alternative has been positive.

6.4.1.3 Cost

The cost of Alternative 1 is summarized in Table 6.3. Capital costs are limited to the construction of three new POC wells and one new LTM well. Included in the $200,000 total present worth cost estimate for Alternative 1 are the costs of maintaining institutional controls and long-term ground water monitoring for a total of 20 years.

TABLE 6.3

ALTERNATIVE 1 - COST ESTIMATE
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Capital Costs	**Cost**
Design/Construct Three POC Wells and One LTM Well	$13,500
Operation, Maintenance and Monitoring Costs (Annual)	**Annual Cost**
Conduct Annual Ground Water Monitoring of 7 wells (20 years)	$3,000
Maintain Institutional Controls/Public Education (20 years)	$6,000
Project Management and Reporting (20 years)	$6,000
Present Worth of Alternative 1 [a/]	**$200,000**

[a/] Based on an annual inflation factor of 5 percent.

6.4.2 Alternative 2 - Bioventing, Biosparging, Intrinsic Remediation and Institutional Controls with Long-Term Ground Water Monitoring

6.4.2.1 Effectiveness

Addition of oxygen to vadose zone soil in the source areas will mitigate further plume migration by stimulating biodegradation of BTEX compounds and reducing the mass of BTEX that dissolves into site ground water. In addition, the bioventing/biosparging system should increase the oxygen flux across the water table, stimulating additional biodegradation of dissolved BTEX compounds. Dissolved BTEX downgradient of the system would continue to be reduced by intrinsic remediation alone. Given the Bioplume II model results discussed in Section 5, reduction in the mass of BTEX compounds that dissolve into ground water should further limit plume migration and ultimately reduce the extent of the dissolved BTEX plume. As with Alternative 1, this alternative would require long-term land use restrictions and enforcement

of health and safety plans to reduce risks from installing the bioventing system and installing and monitoring LTM and POC wells.

Alternative 2 should provide reliable, continuous protection with little risk from temporary system failures. This alternative also complies with the program goals because intrinsic remediation remains the predominant decontamination method for the site. However, this remedial alternative will result in the generation of additional drill cuttings and other wastes requiring treatment and/or disposal.

It is assumed that dissolved benzene concentrations will exceed state ESs throughout the plume for approximately 10 years under Alternative 2. An additional 5 years of annual ground water monitoring will be required to ensure that biosparging and intrinsic remediation has uniformly reduced all BTEX compounds to levels below ESs. Costs for installation of the bioventing system are based on the conceptual design discussed in Section 6.3.2.

6.4.2.2 Implementability

Installing and operating a bioventing system (with or without biosparging) to reduce source area BTEX concentrations at the Truax Field site will present additional implementability concerns. Installation involves standard drilling practices for wells, and limited shallow excavation for piping and manifold connections. Implementation in and around the POL yard could be disruptive to fueling operations. Bioventing equipment is readily available and the technology used to construct the system is proven and reliable. The technical and administrative implementability concerns associated with the intrinsic remediation and LTM component of this remedial alternative are similar to those discussed in Alternative 1. Installation and operation of a full-scale bioventing system would require an increased commitment of man-hours and other resources to maintain and monitor the system.

6.4.2.3 Cost

The estimated capital and operating costs of Alternative 2 are shown in Table 6.4. The total present worth cost of Alternative 2 is $472,000. The cost of Alternative 2 will be increased from the costs of Alternative 1 by the addition of bioventing (with or without biosparging). It is assumed that the bioventing system will operate for 4 years after installation. Annual LTM would continue for 15 years to ensure that intrinsic remediation is reducing BTEX concentrations below ESs throughout the plume and to verify that contamination does not reach the POC wells.

TABLE 6.4

ALTERNATIVE 2 - COST ESTIMATE
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Capital Costs	**Cost**
Design/Construct Three POC Wells and One LTM Well	$13,500
Design/Construct Bioventing/Biosparging System, Including Manifolding and Blowers (assuming 20 wells @ 10 feet deep)	$260,000
Operation, Maintenance and Monitoring Costs (Annual)	**Annual Cost**
Operate and Maintain Bioventing System (4 years)	$12,000
Conduct Annual Ground Water Monitoring of 7 wells (15 years)	$3,000
Maintain Institutional Controls/Public Education (15 years)	$6,000
Project Management and Reporting (15 years)	$6,000
Present Worth of Alternative 2 [a/]	**$472,000**

[a/] Based on an annual inflation factor of 5 percent.

6.5 RECOMMENDED REMEDIAL APPROACH

Two remedial alternatives have been evaluated for remediation of the shallow ground water at the Truax Field site. Components of the alternatives evaluated include bioventing, intrinsic remediation with LTM, and institutional controls. Table 6.5 summarizes the results of the evaluation based upon effectiveness, implementability, and cost criteria. On the basis of this evaluation, Parsons ES recommends Alternative 1 as achieving the best combination of risk reduction and cost effectiveness.

Both alternatives make maximum use of intrinsic remediation mechanisms to reduce plume migration and toxicity. Alternative 2 would provide additional protection against

TABLE 6.5

SUMMARY OF REMEDIAL ALTERNATIVES EVALUATION
GROUND WATER REMEDIATION
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Remedial Alternative	Effectiveness	Implementability	Present Worth Cost Estimate
Alternative 1			$200,000
- Intrinsic Remediation - Long-Term Monitoring	Contaminant mass, volume, and toxicity will be significantly reduced and plume migration should be halted. MCLs for BTEX not likely to be exceeded at POC wells.	Readily implementable. Long-term management, ground water use controls and monitoring required for an estimated 20 years. Minimal exposure of site workers if excavation is carefully controlled in source area. If MCLs are exceeded at POC, additional remedial work may be required.	
Alternative 2			$472,000
- Bioventing/Biosparging - Intrinsic Remediation - Long-Term Monitoring	Similar to Alternative 1, with the addition of a bioventing system (with or without biosparging) to address residual LNAPL in soil. Contaminant mass, volume, and toxicity will be reduced more rapidly than in Alternative 1. Less likely that MCLs will be exceeded at POC.	Readily implementable. Installation of a bioventing system should pose no problems. Bioventing estimated to continue for 4 years. Long-term management, ground water controls, and monitoring required for an estimated 15 years. If MCLs are exceeded at POC, additional remedial work may be required.	

further plume migration, but would still rely on intrinsic remediation mechanisms to reduce plume toxicity downgradient of the bioventing system. Implementation of Alternative 2 would decrease the time frame for remediation, but would require a greater capital expenditure.

Both of the remedial alternatives are implementable, and both alternatives effectively reduce potential hydrocarbon migration and toxicity. Both alternatives should be acceptable to the public and regulatory agencies because they are protective of human health and the environment and reduce soil and ground water contamination in a relatively short time frame. Implementation of either alternative will require land use and ground water use controls to be enforced for at least 15 years, along with annual ground water monitoring for the same period.

The final evaluation criterion used to compare each of the two remedial alternatives was cost. It is the opinion of Parsons ES that the additional cost of Alternative 2 over Alternative 1 is not justified by the minimal additional protection it provides. Therefore, Alternative 1 is recommended.

SECTION 7

LONG-TERM MONITORING PLAN

7.1 OVERVIEW

In keeping with the requirements of the preferred remedial alternative for the Truax Field site (intrinsic remediation with LTM), a long-term ground water monitoring plan must be developed. The purpose of this component of the preferred remedial alternative for the site is to assess site conditions over time, confirm the effectiveness of naturally occurring processes at reducing contaminant mass and minimizing contaminant migration, and evaluate the need for additional remediation.

The LTM plan consists of identifying the location of two separate ground water monitoring networks and developing a ground water sampling and analysis strategy to demonstrate attainment with both levels of site-specific remediation goals and to verify the predictions of the Bioplume II model developed for the Truax Field site. The strategy described in this section is designed to monitor plume migration over time and to verify that intrinsic remediation is occurring at rates sufficient to protect potential receptors. In the event that data collected under this LTM program indicate that naturally occurring processes are insufficient to protect human health and the environment, contingency controls to augment the beneficial effects of intrinsic remediation would be necessary.

7.2 MONITORING NETWORKS

Two separate sets of wells will be utilized at the site as part of the intrinsic remediation with LTM remedial alternative. The first set will consist of four LTM wells located in, upgradient, and downgradient of the observed BTEX plume to verify the results of the Bioplume II modeling effort and to ensure that natural attenuation is occurring at rates sufficient to minimize plume expansion (i.e., meet the first level of remediation concentration goals for the site). This network of wells will consist of three existing wells and one

proposed well screened within the shallow aquifer to provide short-term confirmation and verification of the quantitative ground water modeling results. The second set of three ground water monitoring wells will be located along a line perpendicular to the direction of ground water flow approximately 400 feet downgradient from the September 1994 plume front (the POC for this demonstration project). The purpose of the POC wells is to verify that no BTEX concentrations exceeding state ESs migrate beyond the area under institutional control. Although model results suggest that the plume front should migrate less than 250 feet downgradient from the source area, the greater distance was selected to avoid installation of POC wells in streets or parking areas. This network will consist of three ground water monitoring wells screened across the first 10 feet of the shallow aquifer. The LTM and POC wells will be sampled for analysis of the parameters listed in Tables 7.1 and 7.2, respectively.

7.2.1 Long-Term Monitoring Wells

At four locations, ground water wells within, upgradient, and downgradient from the existing BTEX contaminant plume will be used to monitor the effectiveness of intrinsic remediation in reducing total contaminant mass and minimizing contaminant migration at the Truax Field site. One well upgradient from the existing plume will be monitored. Of the remaining wells, typically one is placed within the anaerobic treatment zone, one is placed in the aerobic treatment zone, and one is placed downgradient of the aerobic treatment zone. However, because the aerobic treatment zone is not well defined, wells will not be placed in this manner. Instead, one well near the plume core and wells at two downgradient locations within and just beyond the existing BTEX plume will be monitored.

At three of the locations, existing wells will be used for this purpose. Well MW-25 will be used to monitor conditions upgradient of the plume, while monitoring point CPT17S will be used to monitor conditions near the plume core. Monitoring well MW-16 will be used for monitoring nearer the downgradient plume boundary. For monitoring downgradient of the plume, one new permanent well should be installed. In addition, regulatory requirements may dictate installation of a new well (constructed according to specifications set forth in section NR141 of the Wisconsin Administrative Code) at the location of CPT17S. Figure 7.1 identifies the proposed locations of the new well and the existing wells to be used for LTM. This network will supplement the POC wells to provide early confirmation of model

TABLE 7.1

LONG-TERM MONITORING ANALYTICAL PROTOCOL
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Ferrous Iron (Fe^{2+})	Colorimetric A3500-Fe D	Field only	Elevated ferrous iron concentrations may be indicative of the anaerobic biodegradation process of iron reduction	Annually	Collect 100 mL of water in a glass container; acidify with hydrochloric acid per method	Field
Ferrous Iron (Fe^{2+})	Colorimetric HACH 25140-25	Alternate method; field only	Elevated ferrous iron concentrations may be indicative of the anaerobic biodegradation process of iron reduction	Annually	Collect 100 mL of water in a glass container	Field
Temperature	E170.1	Field only	Metabolism rates for microorganisms depend on temperature	Annually	N/A	Field
Dissolved Oxygen	Dissolved oxygen meter	Refer to Method A4500 for a comparable laboratory procedure	The oxygen concentration is a data input to the Bioplume II model; concentrations less than 1 mg/L generally indicate an anaerobic pathway	Annually	Collect 300 mL of water in biochemical oxygen demand bottles; analyze immediately; alternately, measure dissolved oxygen in situ	Field
pH	E150.1/SW9040, direct reading meter	Protocols/Handbook methods[a/]	Aerobic and anaerobic processes are pH-sensitive	Annually	Collect 100–250 mL of water in a glass or plastic container; analyze immediately	Field
Conductivity	E120.1/SW9050, direct reading meter	Protocols/Handbook methods	General water quality parameter used as a marker to verify that site samples are obtained from the same ground water system	Annually	Collect 100–250 mL of water in a glass or plastic container	Field
Nitrate (NO_3^{-1})	IC method E300 or method SW9056; colorimetric, method E353.2	Method E300 is a Handbook method; method SW9056 is an equivalent procedure	Substrate for microbial respiration if oxygen is depleted	Annually	Collect up to 40 mL of water in a glass or plastic container; cool to 4°C; analyze within 48 hours	Fixed-base

TABLE 7.1 (Concluded)

LONG-TERM MONITORING ANALYTICAL PROTOCOL
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Sulfate (SO_4^{2-})	IC method E300 or method SW9056 or HACH SulfaVer 4 method	Method E300 is a Handbook method; method SW9056 is an equivalent procedure. HACH method is Photometric	Substrate for anaerobic microbial respiration	Annually	Collect up to 40 mL of water in a glass or plastic container; cool to 4°C	Fixed-base or field (for HACH method)
Redox potential	A2580 B	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	The redox potential of ground water influences and is influenced by biologically mediated reactions; the redox potential of ground water may range from more than 200 mV to less than -400 mV	Annually	Collect 100–250 mL of water in a glass container, filling container from bottom; analyze immediately	Field
Methane	RSKSOP-114 modified to analyze water samples for methane by headspace sampling with dual thermal conductivity and flame ionization detection.	Method published and used by the US Environmental Protection Agency Robert S. Kerr Laboratory	The presence of methane suggests BTEX degradation via an anaerobic pathway utilizing carbon dioxide (carbonate) as the electron acceptor (methanogenesis)	Annually	Collect water samples in 40 mL volatile organic analysis (VOA) vials with butyl gray/Teflon-lined caps (zero headspace); cool to 4°C	Fixed-base
Aromatic hydrocarbons (BTEX)	Purge and trap GC method SW8020	Handbook method; analysis may be extended to higher molecular weight alkylbenzenes	BTEX are the primary target analytes for monitoring natural attenuation; BTEX concentrations must also be measured for regulatory compliance	Annually	Collect water samples in a 40 mL VOA vial with zero headspace; cool to 4°C; add hydrochloric acid to pH ≤ 2	Fixed-base

a/ Protocol methods are presented by Wiedemeier *et al.* (1994).

TABLE 7.2

POINT-OF-COMPLIANCE MONITORING ANALYTICAL PROTOCOL
REMEDIAL ACTION OPTION EVALUATION
WISCONSIN AIR NATIONAL GUARD AT TRUAX FIELD
MADISON, WISCONSIN

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Temperature	E170.1	Field only	Well development	Annually	N/A	Field
Dissolved Oxygen	Dissolved oxygen meter	Refer to method A4500 for a comparable laboratory procedure	The oxygen concentration is a data input to the Bioplume model; concentrations less than 1 mg/L generally indicate an anaerobic pathway	Annually	Collect 300 mL of water in biochemical oxygen demand bottles; analyze immediately; alternately, measure dissolved oxygen in situ	Field
pH	E150.1/SW9040, direct reading meter	Protocols/Handbook methods[a/]	Aerobic and anaerobic processes are pH-sensitive	Annually	Collect 100–250 mL of water in a glass or plastic container; analyze immediately	Field
Conductivity	E120.1/SW9050, direct reading meter	Protocols/Handbook methods	General water quality parameter used as a marker to verify that site samples are obtained from the same ground water system	Annually	Collect 100–250 mL of water in a glass or plastic container	Field
Redox potential	A2580 B	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	The redox potential of ground water influences and is influenced by biologically mediated reactions; the redox potential of ground water may range from more than 200 mV to less than -400 mV	Annually	Collect 100–250 mL of water in a glass container, filling container from bottom; analyze immediately	Field
Aromatic hydrocarbons (BTEX)	Purge and trap GC method SW8020	Handbook method; analysis may be extended to higher molecular weight alkylbenzenes	BTEX are the primary target analytes for monitoring natural attenuation; BTEX concentrations must also be measured for regulatory compliance	Annually	Collect water samples in a 40 mL VOA vial with zero headspace; cool to 4°C; add hydrochloric acid to pH ≤2	Fixed-base

[a/] Protocol methods are presented by Wiedemeier *et al.* (1994).

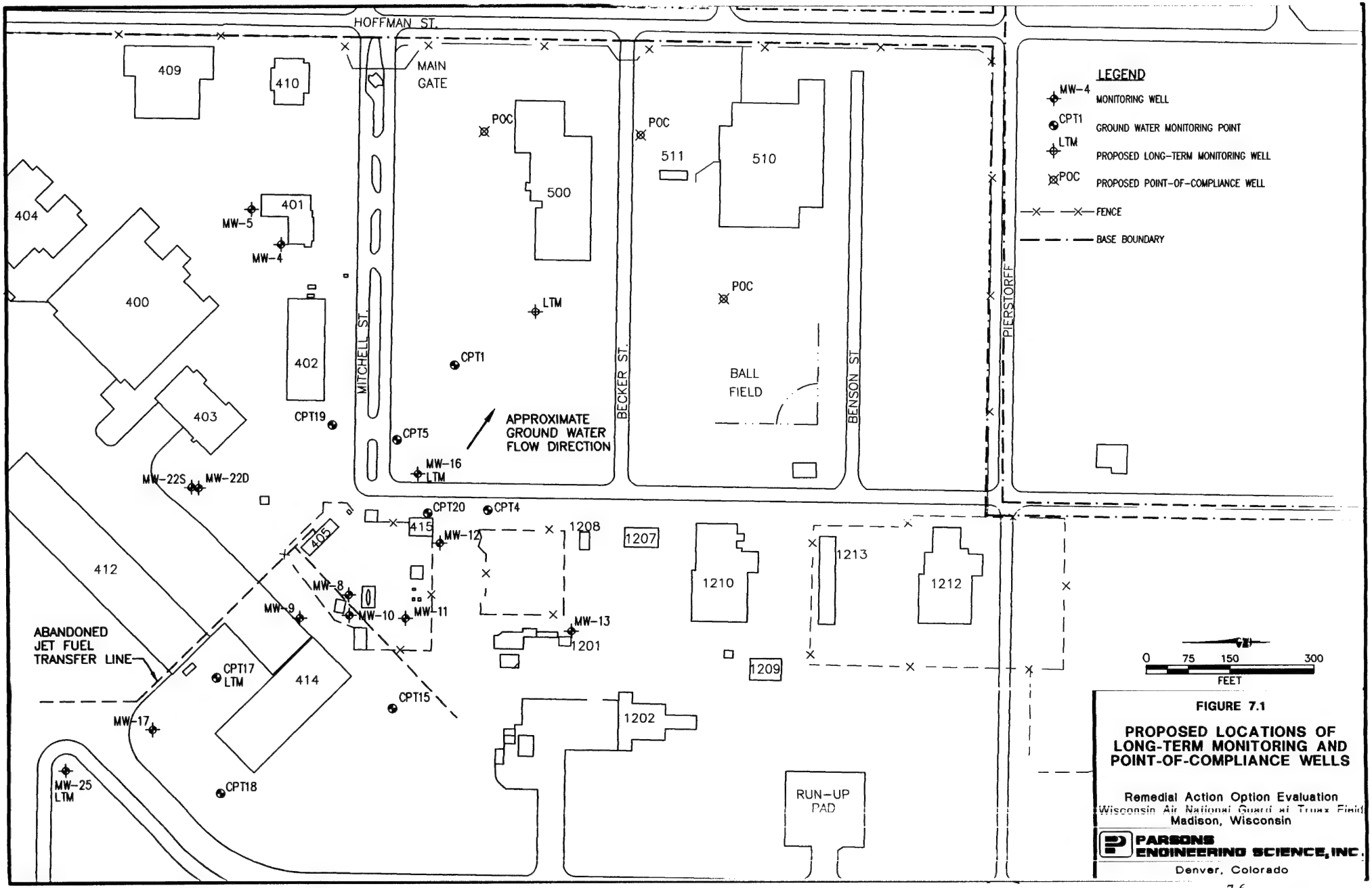

FIGURE 7.1

PROPOSED LOCATIONS OF LONG-TERM MONITORING AND POINT-OF-COMPLIANCE WELLS

Remedial Action Option Evaluation
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Madison, Wisconsin

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predictions and to allow additional response time if necessary. The new LTM well will be constructed with a 10-foot screen, with approximately 8 feet of the screen below the water table. All LTM wells will be sampled and analyzed for the parameters listed in Table 7.1 to verify the effectiveness of the intrinsic remediation remedial alternative.

7.2.2 Point-of-Compliance Wells

Three POC monitoring wells will be installed approximately 400 to 450 feet downgradient of the existing BTEX plume. Figure 7.1 shows the proposed locations of these wells. The purpose of the POC wells is to verify that no contaminated ground water exceeding state ESs migrates beyond the area under institutional control. Although model results suggest that the contaminant plume will not migrate beyond this location at concentrations exceeding chemical-specific federal MCLs, these POC wells are the technical mechanisms used to demonstrate protection of human health and the environment and compliance with site-specific numerical remediation goals. These wells will be installed and monitored for the parameters listed in Table 7.2 to assure that the selected remedy is providing the anticipated level of risk reduction and remediation at the site.

As with the LTM wells, the POC wells will also be screened in the same hydrogeologic unit as the contaminant plume. Data presented in this report concerning the nature and extent of contamination at the site suggest that a 10-foot screen with approximately 8 feet of screen below the ground water surface will be sufficient to intercept the contaminant plume at this site. Figure 7.2 is a proposed ground water monitoring well completion diagram for both the LTM wells and the POC wells.

7.3 GROUND WATER SAMPLING

To ensure that sufficient contaminant removal is occurring at the Truax Field site to meet site-specific remediation goals, the long-term ground water monitoring plan includes a comprehensive sampling and analysis plan. Both LTM and POC wells will be sampled and analyzed annually to verify that naturally occurring processes are effectively reducing contaminant mass and mobility. Reductions in toxicity will be implied by mass reduction. The sampling and analysis plan will also be aimed at assuring intrinsic remediation can

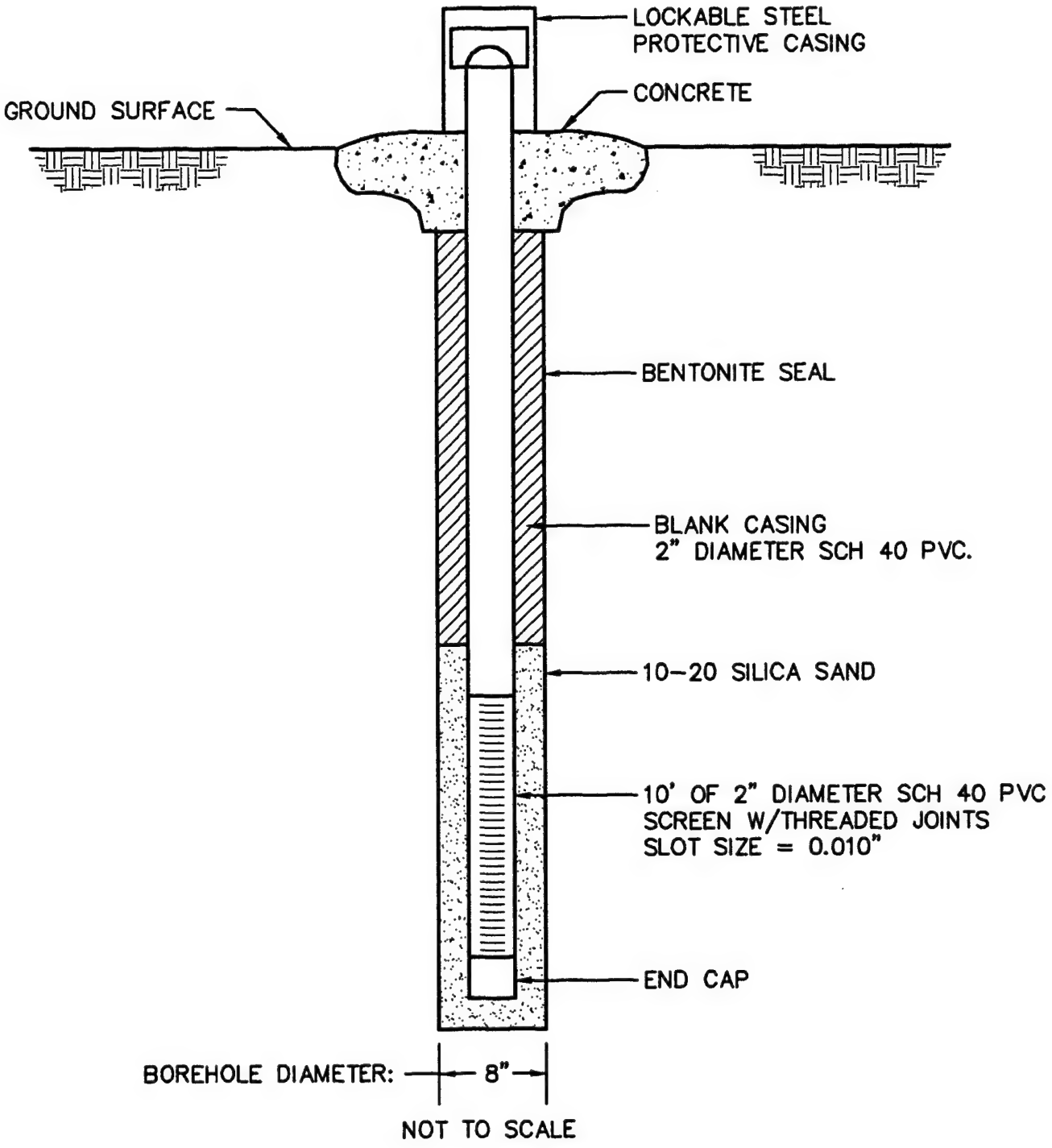

FIGURE 7.2

PROPOSED MONITORING WELL COMPLETION DIAGRAM

Remedial Action Option Evaluation
Wisconsin Air National Guard at Truax Field
Madison, Wisconsin

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

achieve site-specific remediation concentration goals for BTEX compounds that are intended to be protective of human health and the environment.

7.3.1 Analytical Protocol

All LTM and POC wells in the LTM program will be sampled and analyzed to determine compliance with chemical-specific remediation goals and to verify the effectiveness of intrinsic remediation at the site. Water level measurements will be made during each sampling event. Ground water samples will be analyzed for the parameters listed in Tables 7.1 and 7.2. A site-specific ground water sampling and analysis plan should be prepared prior to initiating the LTM program.

7.3.2 Sampling Frequency

Each of the LTM and POC sampling points will be sampled once each year for 20 years. If the data collected during this time period supports the anticipated effectiveness of the intrinsic remediation alternative at this site, the sampling frequency could be reduced to once every other year for all wells in the LTM program, or sampling could be eliminated outright. If the data collected at any time during the monitoring period indicate the need for additional remedial activities at the site, sampling frequency should be adjusted accordingly.

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

This report presents the results of an RAE conducted to evaluate the use of intrinsic remediation (natural attenuation) for remediation of fuel-hydrocarbon-contaminated ground water in the vicinity of Building 412 and the POL yard at the Wisconsin Air National Guard Base at Truax Field, Wisconsin. Specifically, the finite-difference ground water model Bioplume II was used in conjunction with site-specific geologic, hydrologic, and laboratory analytical data to simulate the migration and biodegradation of fuel hydrocarbon compounds dissolved in ground water. To collect the data necessary for the intrinsic remediation demonstration, Parsons ES researchers collected soil and ground water samples from the site. Physical and chemical data collected under this program were supplemented (where necessary) with data collected during previous site characterization events.

Comparison of BTEX, electron acceptor, and biodegradation byproduct isopleth maps for the Truax Field site provides strong qualitative evidence of biodegradation of BTEX compounds. Geochemical data strongly suggest that biodegradation of fuel hydrocarbons is occurring at the site via aerobic respiration and the anaerobic processes of denitrification, iron reduction, sulfate reduction, and methanogenesis. In addition, patterns observed in the distribution of hydrocarbons, electron acceptors, and biodegradation byproducts further indicate that biodegradation is reducing dissolved BTEX concentrations in site ground water.

Site-specific geologic, hydrologic, and laboratory analytical data were then used in the Bioplume II numerical ground water model to simulate the effects of advection, dispersion, sorption, and biodegradation on the fate and transport of the dissolved BTEX plume. Extensive site-specific data were used for model calibration and implementation. Model parameters that could not be obtained from existing site data were estimated using widely accepted literature values for sediments similar to those found at the site. Conservative aquifer parameters were used to construct the Bioplume II model for this study, and therefore, the model results presented herein represent worst-case scenarios given the other modeling assumptions regarding source removal.

For one simulation (model MAD_B), it was assumed that conditions that produced the calibrated model would persist for the duration of the simulation. This scenario suggests that the plume would migrate a maximum of 250 feet beyond the September 1994 plume front before BTEX migration halts and the plume stabilizes as a result of natural attenuation. Model MAD_C assumed that bioventing in the source areas would reduce BTEX dissolution rates to 10 percent of the calibrated model rates in 3 years. Results of this model suggest that the plume will migrate approximately 100 feet beyond the September 1994 plume margin before natural attenuation mechanisms effectively halt migration and shrink the plume. MAD_C predicts that the BTEX plume will shrink back to the Building 412 source area in less than 10 years.

The results of this study suggest that natural attenuation of BTEX compounds is occurring at the Truax Field site to the extent that the dissolved concentrations of these compounds in ground water should be reduced to levels below current regulatory guidelines long before potential downgradient receptors could be adversely affected (i.e., the potential contaminant migration pathway will not be complete for any of the potential receptors described in Section 6.2). Actual dissolved BTEX degradation rates observed during LTM at the site will probably be less than predicted by model MAD_C and greater than predicted by model MAD_B. This will result in a shorter plume migration distance than predicted by model MAD_B. Given the rates of BTEX plume migration and degradation predicted by models MAD_B and MAD_C, and that there are no identifiable downgradient receptors within the plume extents predicted by model MAD_B, Parsons ES is recommending natural attenuation, institutional controls, and LTM as the remedial option for BTEX-impacted ground water at the site. Construction activities in the plume area and ground water use in and downgradient from the plume area should be restricted for a period of approximately 20 years.

To verify the results of the Bioplume II modeling effort, and to ensure that natural attenuation is occurring at rates sufficient to protect potential downgradient receptors, ground water from existing monitoring wells MW-25, MW-16, CPT17S, and one additional proposed LTM well should be sampled annually and analyzed for the parameters listed in Table 7.1. In addition, three POC ground water monitoring wells should be installed downgradient from the predicted maximum travel distance of the BTEX plume and sampled annually for the parameters listed in Table 7.2. Figure 7.1 shows suggested locations for the three new POC monitoring wells and the new LTM well. These wells should be sampled annually for 20 years. If dissolved BTEX concentrations in ground water in the POC wells

exceed state ESs of 5 µg/L for benzene, 343 µg/L for toluene, 1,360 µg/L for ethylbenzene, or 620 µg/L for total xylenes, additional evaluation or corrective action may be necessary at this site.

Once it is decided that the ground water monitoring points installed for this study will not be used for future resampling, they should be abandoned according to the requirements set forth in section NR141.25 of the Wisconsin Administrative Code.

SECTION 9

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